EFFECTS OF FOREST MANAGEMENT ON

SOIL ERODIBILITY

by

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Thesis submitted in partial fulfilment of the requirements for the degree of Master of Science (Forestry) in the Australian National University.

February 1975.

ORIGINALITY OF THESIS

Except where specific acknowledgement is given, this thesis is my original work.

Sein Thet 12/2/75

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ACKNOWLEDGEMENTS

A Colombo Plan Fellowship enabled me to do this study. I am therefore grateful to the Colombo Plan authorities in Burma as well as to my host country, Australia; especially to the Departments of External Affairs and Education of the Commonwealth Government of Australia, for their interest in my welfare and academic progress during my stay in Australia. I am indebted to the Forest Department, the Socialist Republic of the Union of Burma, for the nomination to this study post. The authorities of the Australian National University, especially Professor J.D. Ovington who was Head of the Department of Forestry (now First Assistant Secretary of the Department of Environment and Conservation) provided me the facilities used in this study and are gratefully acknowledged.

In particular, I not only wish to acknowledge, but sincerely thank my supervisors:- Dr P.R. Stevens, initial supervisor, for his interest, constructive criticism and helpful advice, and Mr D.M. Stodart, later supervisor, for his critical comments, helpful advice and assistance in field inspection and subsequent work in the writing up of the thesis. My very sincere thanks are due to Miss R.W. Purdie who assisted with the English and field work and for her encouragement.

I am also indebted to, and would like to thank the following:-

- Dr M.T. Tanton for draft reading, helpful comments and advice on statistical analysis of the data.
- Mr T.S. Johnson and Mr D.J. Smith for their assistance on the statistical analysis of data.

- Mr F.J. Darlington who gave much helpful advice and assistance with instrumentation during soil analytical work.
- Mr H.M.G. Thomas for helping in extraction and identification of soil invertebrates.
- A.C.T. Forests Branch, for permission to conduct field work in Pierces Creek Forest and to extract information from Branch Records.
- Mrs P. Reid for her helpful assistance in finding the literature, and
- Mrs E.H. Robinson for typing of the thesis.

I am also grateful to the staff and fellow students of the Department of Forestry, Australian National University, for their enjoyable, very friendly association. Thanks are also due to those Australian families whose homes the author visited, received sincere hospitality and discussion which provided a great deal of opportunities to understand things other than those learned from university education.

Finally I am deeply indebted to my wife "Saw" for her encouragement and self-sacrifice throughout the long period of my absence from home for this study.

TABLE OF CONTENTS

Page No.

Page No.

Page No.

Page No.

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 GENERAL INTRODUCTION

Soil erosion is "the process of detachment and transportation of soil materials by erosive agents". It is influenced by the amount and intensity of rainfall and wind, the slope of the land, the type and condition of vegetative cover, and the nature and properties of the soil and, except in the true deserts and the frozen polar regions, land is subject to water erosion during rains if the soil is uncovered.

Forests are very effective in controlling erosion, especially if they are undisturbed. The tree canopy intercepts rainfall and reduces its energy. Drops that reach the ground are quickly taken-up in the leaf litter and from there into the highly porous soil surface. However, forests can only control erosion effectively if they are properly managed (Kohnke and Bertrand, 1959). The major reasons for soil erosion are improper cultivation methods and mismanagement of tree and herbaceous vegetation, which leave the soil stripped of protection and hence susceptible to erosion by wind and water (Brown et. al.,1968). The protection of the soil from erosion cannot usually be the only purpose of forest management, and multiple-use forest management seeks to provide the maximum benefits both directly and indirectly. Direct benefits include the provision of essential commercial commodities such as structural timber, pulpwood, plywood, veneers, firewood, bark products, tars, oils and resins and other minor forest produce, such as honey. Indirect benefits include protection of soil and stock from wind and exposure, regulation of stream flow, provision of recreational facilities and aesthetic effects.

The intensity of use and management of forest lands has increased with development and population increases and in some countries plantations have been established with exotic species to increase wood production. This study is concerned with the effects of the establishment of *Pinus radiata* plantations on the erodibility of soils that formerly carried eucalypt forest.

1.2 BACKGROUND

Australia is one of the oldest countries geologically, but agriculturally it is young (Clayton, 1954). Before the advent of white man, in 1788, many of the hills and valleys were covered with dense forest or grass and although some erosion occurred, as is evident in the eroded horizons of some alpine soils, the natural balance was upset by the new settlers and accelerated erosion occurred as large areas of land were cleared unwisely for pasture and for cultivation.

Australia's erosion problems now lie principally in three fields:-

(1) the arable areas used predominantly for wheat-growing and damaged by both wind and water erosion;

(2) the highland grazing areas, with adequate rainfall but over-grazed and with insufficient attention to pasture development;

(3) the arid pastoral areas where pasture development or stimulation has so far proved impracticable and severely overgrazed (FAO, 1953).

An outline of the historical aspects of soil erosion in Australia and its control followed by a brief discussion of the principles of prevention of erosion is found in Condon (1972).

The first major governmental move to correct the serious soil erosion in Australia was the formation of a Soil Erosion Committee by the New South Wales Government in 1933. Further progress towards the formation of state soil conservation organisations was made after the 5th Meeting of the Australian Agricultural Council in August 1937, and in 1946, a Commonwealth Standing Committee on Soil Conservation was established on the recommendation of the Agricultural Council. The standing committee consisted of heads of the State Soil Conservation Organisations, representatives from the former Commonwealth Departments of Primary Industry and Interior and the Commonwealth Scientific and Industrial Research Organisation. The main functions of the committee are to co-ordinate the works of the state soil conservation services, to obtain the co-operation and assistance of trained personnel in the related fields and to undertake special research projects.

Pine planting to control erosion began in the second decade of this century in several bare areas where erosion had been accelerated by over-grazing and over-clearing, for example in the Uriarra and Pierces Creek forests in the A.C.T.

The Australian Forestry Council after its establishment in 1964, agreed that Australia should aim for an overall planting rate of 30,300 ha (75,000 acres) per year to provide a total of 1.2 million ha (3 million acres) of plantation to make the country self-sufficient in softwood by the year 2000. The present coniferous plantations cover nearly half a million hectares (Table 1.1).

TABLE 1.1 Coniferous Plantation Areas as at 31 March 1972 (net hectares)

State or Territory	Crown Land	Private Property	Grand Total
New South Wales	85,879	17,171	103,050
Victoria	50,194	55,648	105,842
Queensland	77,090	19,545	96,635
South Australia	69,754	16,417	86,171
Western Australia	30,001	3,858	33,859
Tasmania	19,137	7,838	26,975
Australian Capital Territory	12,698	-	12,698
Northern Territory	2,671	20	2,691
Total	347,424	120,497	467,921

- Nil or Negligible Source: Based on Forestry and Timber Bureau Annual Report 1972/73.

A high proportion of the plantation programme involves a change in forest type from eucalypt to conifer and thus if there are significant changes in soil erodibility characteristics as a consequence of plantation establishment the changes may occur over a large area.

1.3 AIMS OF THE STUDY

Given that plantation establishment has been used as a soil erosion control measure and that large areas of plantation will be established for wood production purposes it was decided to examine the effects of such land use changes on soil properties related to erodibility. The following situations are considered in this context:-

(i) Areas afforested with pines and native hardwoods (Eucalypts);

(ii) Areas severely disturbed and eroded and now revegetated;

(iii) Areas with contrasting soils, slopes and parent material on which similar forests have established.

CHAPTER 2

REVIEW OF LITERATURE

2.1 INTRODUCTION

Ellison (1947) defined soil erosion as "the process of detachment and transportation of the soil material by erosive agents". Deposition is the result of soil erosion. Detachment, transportation and deposition are natural processes but can be caused by human activities for example mining, over-grazing, burning, over-cutting of forests, and civil engineering construction works such as dams and roads.

Erosion which takes place under natural conditions is variously known as normal, natural or geologic erosion, while erosion due to human activities is known as accelerated erosion or simply, EROSION. Water and wind are the main natural agents of erosion. Water erosion is active in all regions, arid as well as humid. Erosion by wind is most active in arid and semi-arid regions. Henceforth the term "erosion" will apply only to accelerated erosion by water. (Vocabulary of soil science including erosion is given in Appendix I).

2.2 THE EROSION PROCESS

Erosion is a work process, caused by the falling raindrops and surface run-off. The process begins when raindrops strike the surface of the soil and break down the clods and aggregates. During rainfall, both falling raindrops and flowing water are active in loosening and transporting the loose soil particles. Detachment may occur without transportation but transportation can only follow detachment. Maximum erosion occurs when the detaching capacities of rainfall and surface flow are at least balanced by the transporting capacity. The major types of erosion are:-

(i) Sheet erosion, the removal of surface soil over large areas;

(ii) Gully erosion: the soil and subsoil is gouged out in localized areas to produce gullies;

(iii) Tunnel erosion: the sub-soil is washed downhill beneath the surface with a subsequent collapse of the unsupported surface soil;

(iv) Stream or channel erosion: the undermining and subsidence of the banks of rivers and creeks.

2.3 PHYSICAL CONDITIONS AFFECTING SOIL EROSION

Systematic valuation of the factors affecting erosion started in the 1930's. Baver (1933) recognised that the severity of erosion depended upon the action and interaction of climate, vegetation, topography and soil. Later, in 1956, he included human activities and summarised the factors affecting erosion in the form:-

$$E = f(C,T,S,V,H)$$

where E = Erosion

C = Climatic factor

T = Topographic factor

S = Soil factor

V = Vegetative factor and

H = Human factor.

These are still accepted as the main physical factors affecting erosion.

2.3.1 Topography

Topographic features are of outstanding importance in the erosion process, because they influence the amount and rate of both run-off and erosion. The topographic features influencing erosion are the steepness, the length and the curvature of slope.

2.3.1.1 Slope Steepness

The velocity of run-off increases with slope steepness and the power to detach, pick up and transport soil materials also increases and soil loss therefore increases with steepness.

Neal (1938) used simulated rainfall and a constant length of slope to determine the effect of the steepness of slope on soil erosion and found that soil-loss was a function of the degree of slope to the power 0.7. In contrast, values double this have been reported, with soil-loss depending on the degree of slope to the power 1.4 (Zingg, 1940). From the analysis of available data Smith and Wischmeier (1957) developed an equation which is used to evaluate the slope factors of the universal soil-loss equation, that is:-

$$A = 0.43 + 0.30\,S + 0.043\,S^2$$

where A = soil loss and

S = slope percent.

2.3.1.2 Slope Length

Soil-loss from plots of different lengths revealed comparatively higher erosion from shorter plots than from longer plots when rainfall was light, but higher erosion from longer slopes than shorter slopes when rainfall was heavy (Duley and Akerman, 1934). From an analysis of the existing data Zingg (1940) concluded that soil-loss from fields was a function of slope-length to the power 1.6. Slope-length to the power 1.37 was suggested by Musgrave (1947) to evaluate soil-loss from the field. Van Doren and Bartelli (1956) also used 0.38 for estimating soil-loss per unit area. However a group study at Purdue University in 1956 concluded that for field use the value of the length exponent should be 0.5 ± 0.1 (Smith and Wischmeier, 1957).

2.3.1.3 Slope Curvature

In relation to initial slope shape, sediment load and depth of erosion is greater for convex slopes than for concave, uniform and complex slopes. Concave slopes showed the least sediment load and erosion depth (Meyer and Kramer, 1968). Garde and Van Doren (1949) suggested that the sequence of adjoining segments was more important than the steepness and length of slopes in the case of slopes combining both convex and concave surfaces.

2.3.2 Climate

The main climatic factors that directly or indirectly affect erosion are rainfall and temperature. Wind also affects the process of water erosion by providing a greater drop impact velocity which gives higher energy to displace soil material.

2.3.2.1 Rainfall

Rainfall is the initiating factor in the water erosion process. The amount, intensity, duration and distribution of rainfall, and the characteristics of rain-drops (shape, size, and velocity of impact) affecting erosion have been extensively studied (Neal and Baver, 1937; Laws, 1940; Marshall and Palmer, 1948; Spilhaus, 1948; Gunn and Kinzer, 1949; Wischmeier and Smith, 1958; Dragoun, 1962; and Rogers et. al., 1967).

Wischmeier (1960) found by multiple regression analysis of plot data that the variable EI gave the best indication of a storm's ability to erode soil (E is storm total kinetic energy and I the maximum 30 minute intensity). An excellent review of the effect of raindrop characteristics (raindrop mass, size, size distribution, shape and velocity) and raindrop impact and splash on soil erosion is found in Smith and Wischmeier (1962).

2.3.2.2 Temperature Changes

Temperature is another factor which has much to do with initiating the water erosion process. Daily or seasonal temperature changes affect the soil's physical properties. Temperature changes also affect the viscosity of water and thus infiltration and percolation. The higher the temperature, the lower the viscosity of water and the higher the rate of infiltration and percolation. Grissinger (1966) reported that the stability of cohesive materials decreased as the temperature of the eroding water increased. He gave one example where the rate of erosion at 20°C was about half that at 35°C.

2.3.3 Soil

Soil properties are a function of climate, organisms, relief (topography), parent material, time and their interactions. Soils under similar environments should therefore have similar mechanical, physical and chemical properties, but it has been found in the field that under similar environmental conditions, some soils erode easily while others resist the action of erosive agents. The difference in erodibility has been attributed mainly to the soils inherent physical make-up and the chemical properties.

Bennett (1926) was the first to evaluate by research work the causes of the differences in erodibility of soils. Working in the laterite soils of Cuba, he examined important properties such as texture, structure, organic matter and chemical composition, and showed an apparent relationship between the Silica:Sesqioxide Ratio (the ratio of Al_2O_3 plus Fe_2O_3 to SiO_2) and erosion. He found that the non-friable soil group had a ratio greater than 2, and the friable group less than 2.

In the early 1930's attempts were made, with varying success, to relate some of the easily measurable physical and chemical properties of soil to erosion. The properties of soil related to erodibility can be classified as:-

(i) Those that resist detachability and transporting forces of rainfall and run-off, and

(ii) Those that affect the infiltration rate and permeability.

2.3.3.1 Detachability

In general detachability increases with the size of soil particles, that is, clay particles are more difficult to detach than sand. Resistance to detachment is provided by "water-stable aggregates", that is, the sand, silt and clay particles of the soil are grouped into masses that cling together even though submerged in water (Kohnke, 1966). Eden (1961) considered that loss of structure by the soil was the fundamental cause of soil erosion and subsequent damage and that once crumb structure is destroyed, the percolation of water is impeded and the surface layer is saturated more easily. Loosened particles are bathed, lubricated, and borne away, by water which has to flow over the surface rather than seeping through to lower parts of the soil profile, and to the water table.

The stability of soil crumbs was studied by Emerson (1954 and 1964). He determined their resistance to breakdown in water, and found that the factors governing the breakdown of dry aggregates, when wetted by a liquid, were slaking of the aggregates and dispersion of the clay in the aggregates. The cohesion of the crumb fell very rapidly as wetting occurred and the degree of breakdown caused by the impact of falling rain therefore depends on the cohesive strength of the wet crumbs. Dry soil crumbs, when immersed in water are usually unstable and break up to a varying extent into discrete fragments (slaking) and this break up may proceed one stage further with dispersion i.e. the release of clay.

Adams et. al., (1958) determined the aggregate stability for the 2 to 5 mm size fraction of some Iowa soils, and suggested that soil which breaks down into many very small aggregates, or to primary particles, would be more erodible than soils which break down into intermediate size aggregates, that is, remain stable. Kohnke and Bertrand (1959) summarised the soil properties that reduce detachability as high active organic matter content, high clay content, prevalence of divalent ions among the exchangeable cations, high content of water stable aggregates, high amount of microbial activity, high fertility to stimulate microbes and crops, intermediate moisture content at the beginning of the storm, and consolidated surface.

2.3.3.2 Transportation

When the rate of rainfall exceeds the infiltration rate of water into the soil, water starts to flow over the surface of sloping land and transportation of detached soil particles takes place. With the same velocity of runoff, various soils will erode differently depending on several important soil properties.

The size of the particle (primary or secondary) affects the movement of soil under a given velocity of water. The velocities of water necessary to transport the different soil fractions are: after Baver (1933) -

Silt	0.25 feet per second
Sand	1.00 " " "
Gravel	2.00 " " "

Kohnke and Bertrand (1959) stated that soil properties which reduce transportability are:- high percentage of large primary (sand and gravel) and secondary particles (water-stable aggregates), and high percentage of organic matter. The distance which eroded soil particles travel depends primarily on their size, density and shape, and velocity of runoff water, and to be resistant to transportation, aggregates must be so large that they cannot be floated off easily (Kohnke, 1966).

2.3.3.3 Infiltration

The infiltration rate of a soil is the maximum rate at which a soil, in a given condition at a given time, can absorb rain. Parr and Bertrand (1960) defined it as the volume of water passing into the soil per unit of area per unit of time. The rate of infiltration into a dry soil is usually very rapid for a short time. As the soil becomes wet, the infiltration rate decreases rapidly until it reaches an equilibrium rate. This equilibrium rate depends upon certain soil properties such as texture and structure.

Lewis and Powers (1938) listed a large number of factors affecting infiltration and classified the factors into two major groups:-

(i) those influencing the infiltration rate at a given time and point, such as texture, structure and organic matter;

(ii) those influencing the average infiltration rate over a considerable area and period of time, such as slope, vegetation and surface roughness.

Infiltration into soils also depends on the roughness of surface layers which induces ponding and consequently increases infiltration (Bruce et.al., 1968). Petersen et. al. (1968) investigated the infiltration rates of soils with a high coarse fragment content, and concluded that within a parent material group, content of coarse fragments was the most important factor determining infiltration and available soil moisture.

Sandy soils absorb water rapidly as compared with clays (Baver, 1933). Absorption also increases as soil become more granular; a granular clay soil will absorb water more quickly than the same soil in the non-granulated state due to the relatively high percentage of large pore spaces associated with granulation. The size of the particles at the soil surface is another factor affecting infiltration and erosion (Kohnke and Bertrand, 1959). In general, the greater the sand percentage, the higher the infiltration rate and the lower the runoff and wash erosion. Bryan (1968) also observed that size of textural separates at the surface had a significant effect on infiltration and runoff properties, while non-capillary porosity was important with regard to infiltration.

Infiltration is also dependent on underlying horizons and on the moisture content of the soil at the beginning of the rain. Gilmour (1965) measured surface runoff, soil loss and infiltration on 41 permanent plots covering a range of soil-vegetation types in the Lower Cotter Catchment. A portable rainfall simulator was used in measuring infiltration rates, and the artificial rainfall (at an intensity of 320 points (81 mm) per hour) had drop size and velocity characteristics similar to those of natural rain of the same intensity. Each plot was characterised for type and amount of ground cover, and for the soil physical properties of bulk density, capillary and non-capillary porosity and particle size distribution. He concluded that on soil types with low non-capillary porosity in the subsoil (restricted drainage) the non-capillary porosity of the surface soil was the most important factor in controlling infiltration and surface runoff. Non-capillary porosity of the surface soil was related to weight of ground cover, and reductions in the ground cover below 7.2 t/ha or 0.72 kg/m^2 resulted in a marked increase in surface runoff. On soil types with high non-capillary porosity in the subsoil (even drainage) surface runoff was at a low level at all times, and the amount of ground cover present had little or no effect.

Gilmour also found that infiltration rates were slightly higher under eucalypts, than under pines, that infiltration was lower after dry than wet periods for both eucalypt and pine cover types, and that in dry periods infiltration decreased as ground cover increased. The reverse occurred in wet periods.

2.3.3.4 Permeability

Permeability is the quality or state of a porous medium relating to the readiness with which such a medium conducts or transmits fluids. Quantitatively, it is the property designating the rate at which fluids are transmitted through porous mediums under standard conditions (Parr and Bertrand, 1960).

Bennett (1926) compared the friability and plasticity of certain heavy clay soils in America, with the silica:Sesquioxide ratio of the same soils obtained by chemical analyses made in the laboratory. Soils grouped on the basis of a molecular ratio of less than two proved distinctly more friable in all parts of their profiles, and were much more permeable and resistant to erosion : compared with one another, those soils highest in iron and alumina and lowest in silica were more friable, permeable and less prone to erosion.

Permeability of the different layers in the soil profile plays an important part in the percolation process. Percolation increases with coarseness of texture and the extent of granulation (Baver, 1933). Lutz and Leamer (1939) evaluated the effect of texture and swelling on the permeability of a series of sand separates and sand on several subsoils. In the coarser fractions permeability was found to increase exponentially with an increase in particle size, and in the subsoils an important factor determining permeability was the swelling of the colloidal materials which results in a reduction in the size of the pores. O'Neal (1949) concluded that soil structure was probably the most significant factor in evaluating permeability. However he found that it was difficult to evaluate permeability on the basis of structural factors only and suggested that other characteristics of the structural aggregates and their relation to one another should also be considered.

2.3.3.5 Aggregation

Kemper and Chepil (1965) define an aggregate as a group of two or more primary particles which cohere to each other more strongly than to surrounding particles. Soil masses in which the cohesive forces among particles are greater than the disruptive forces will maintain their identity as aggregates.

Aggregate formation is mainly dependent on organic matter and types of bases in the soil. Divalent cations (e.g. calcium) increase aggregation; monovalent cations (e.g. sodium) decrease aggregation and disperse the soil. The mechanism of aggregate formation is not well understood but depends on clay, organic matter, divalent cations and drying. One explanation (Kemper and Chepil, 1965) is that clay and organic matter are bonded by divalent cation "bridges". However, McHenry and Russell (1943) found that aggregation increased with increase in clay content and that monovalent ions gave better aggregation than divalent ions, which in turn were better than trivalent ions.

The degree of aggregation (amount of granulation) of a soil plays a very important role in the erodibility of soil. Aggregation increases porosity and consequently the rate of water absorption and percolation, and decreases the ease of dispersion making it more difficult to detach the soil particles so that a higher velocity is required to transport soil (Baver, 1933). Bennett (1955) pointed out that coarsely aggregated structures have larger pores, and consequently greater water-intake capacity as well as greater absorption (water retention) capacity. Harris (1971) by determining total and natural clay* by the pipette method, reported that collapse of soil aggregates results in surface sealing, increased run-off and the

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* The "natural clay" is the percentage of clay obtained by using distilled water instead of dispersing solution plus distilled water.

production of fine particles which can then be removed by the surface water. The result is rapid erosion by sheet wash and splashing.

Gerdel's (1937) field observations and laboratory studies indicated that the erodible properties of some residual soils of sandstone, shale, and limestone origin vary with the amount, kind, and stability of the soil aggregates and that the variations may also be influenced materially by previous erosion and cultural practices.

Aggregate size distribution is important in relation to soil erodibility because aggregates below a certain size may be removed by erosion without previous dispersion, and therefore the percentage-weight of aggregates or separates below a particular value is a direct index of erodibility. Aggregate stability is also important because it governs the ease with which large aggregates above the erosion threshold (the actual value at which erosion starts) may be broken down to small aggregates or separates, which are then vulnerable to erosion (Bryan, 1968).

Maximum stability in the soil aggregates occurs during the summer with decreasing stability during the autumn and winter and then an increase in the spring, in several red-brown earths after being treated with pyrophosphate and periodate (Stefanson, 1971).

2.3.3.6 Topsoil Depth

Topsoil depth affects soil erodibility in several ways. Topsoil is usually relatively homogenous and allows water infiltration to proceed unrestricted until layers of different porosity are reached. Another effect is on the organic matter content of the surface.

If the topsoil is thin and the subsoil is mixed with it, for example by ploughing, the organic matter content is lowered. This results in lower aggregate stability and higher erosion. Another effect is on the general fertility status of the soil. The deeper the topsoil, the greater the soil fertility and the improved vegetative cover minimises erosion.

2.3.3.7 Water Holding Capacity

The effect of water-holding capacity on erosion is almost indistinguishable from the effect of texture for this largely determines water-holding capacity. Water-holding capacity has an influence on the amount of water which may run off during heavy rains, as does the amount of water held at the time rain begins, and also on the detachability of soil by runoff water. Sand with a low water holding capacity is easily detached and washed away under the high velocity of runoff, while clay is less easy to detach and may seal over.

2.4 INDICES OF SOIL ERODIBILITY

Soil erodibility may be assessed either by actual measurement of soil loss under controlled conditions, or by the isolation of certain soil properties as indices of erodibility (Bryan, 1968). Measurement of soil loss under controlled conditions requires elaborate installations and observation for lengthy periods, whereas indices of erodibility can usually be derived from normal analytical data and therefore require little special equipment.

Bennett (1926) determined the important soil properties influencing erodibility to be soil texture, structure, organic matter content and chemical composition,although he made no attempt to establish an index of erodibility. Middleton (1930) was the first to attempt to devise an index of erodibility (erosivity) based on detailed laboratory analysis of samples from soils whose reactions to erosional processes were known from field observation, and proposed a "Dispersion Ratio".

2.4.1 Dispersion Ratio

Middleton (1930) found that the amount of silt and clay in a dispersed state was significantly correlated with erodibility. He compared the amount of silt and clay in an undispersed sample with that in a sample previously treated with a dispersing agent. These two results were combined into a ratio which expressed as a percentage was termed the "Dispersion Ratio". Middleton found that it was generally above 15 for "erodible soils" and below 15 for "non-erodible" soils.

Anderson (1951) used the dispersion ratio as an index of erodibility in a study of the erodibility of a lithosequence of youthful soils developed on comparable watersheds in northern Carolina. Erosion was measured as the suspended sediment discharge of streams from the watersheds, and was found to be significantly correlated with dispersion ratio values. Willen (1965) also using the dispersion ratio as an index of erodibility, found an erodibility order of:

granodiorite soils > basalt soils > quartzite soils, in the Sierra Nevada.

Bryan (1968) criticised Middleton's dispersion ratio as being unsatisfactory on two grounds:-

(i) It made no allowance for the ability of high velocity raindrops to disperse previously undispersed material;

(ii) While it may be an accurate index of erodibility of soils with a high silt and clay content, because of its reliance on this measure it would not reflect accurately the erodibility of soils with a high sand content.

2.4.2 Clay Ratio

In 1935 Bouyoucos approached the problem of dispersion from a different angle. In an attempt to arrive at the fundamental principles underlying variations in erodibility, he proposed the "Clay Ratio" as a direct index of erodibility. This is the ratio between sand + silt and clay, and is considered a measure of the amount of binding material. He measured the clay ratio over a wide range of soil types and found a small ratio associated with soils considered to be non-erosive, and the greatest values associated with very erosive soils. A number of workers have tested the clay ratio since its original introduction by Bouyoucos, including Kuron and Jung (1957; in Bryan, 1968) who found that it did not accurately reflect field observations. Bryan (1968) also stated that the index was not entirely satisfactory. He gave the example that soils of the Iredell and Davidson series of North Carolina, which both Middleton (1930) and Lutz (1934) had found to differ considerably in erosional behaviour, gave clay ratio values of 2.5.

While the clay ratio was a logical development of the theory that soil particles must be dispersed before erosion can occur and it has the merit of simplicity and can be derived from basic analytical data, it is open to criticism as an index of erodibility on two grounds:

(i) when the clay content of the soil is very low, the clay ratio is liable to become meaningless due to the high water transmission status. Virtually no runoff will occur, and erosion will be purely a function of splashing by raindrops.

(ii) A more important criticism is that the ratio places undue weight upon the importance of clay as a "binder" and ignores the influence of organic matter, which may be a more important aggregate-cementing agent.

2.4.3 Percentage Weight of Water Stable Aggregate (W.S.A.) and Aggregate Stability

A variety of measures of aggregation have been used as indices of erodibility. Two such measures - aggregate size distribution and aggregate stability - appear to be important. Aggregate size distribution is important because aggregates below a certain size may be removed by erosion without previous dispersion and therefore the relative proportion of aggregates below that size is a direct index of erodibility. Aggregate stability is important because it governs the ease with which large aggregates above the erosion threshold may be broken down to small aggregates vulnerable to erosion.

Adams et. al., (1958) used the dispersion ratio and aggregate stability in a study of the erodibility of some Iowa soils, and compared the results with infiltration rates, runoff and erosion values obtained under simulated rainfall in the field. Stability of the uppermost centimeter of soil was an important factor affecting infiltration and erosion, while the percentage-weight of water stable aggregate greater than 0.10 mm was found to bear no relation to erosion losses.

The percentage-weight of water stable aggregate greater than 2 mm was significantly correlated with erosion losses. Woodburn and Kozachyn (1956) also used aggregate stability and the dispersion ratio as indices of the erodibility of soils in 23 Western Mississippi watersheds. The indices were compared with splash-losses under artificially simulated rainfall as a direct measure of erosion. There was an inverse relationship between the percentage-weight of water stable aggregate greater than 0.5 mm diameter and splash-loss. Wooldridge (1964) used mean water stable aggregate size as an index of erodibility in a study of the effect of parent material and vegetation on soil erosion in Central Washington. Soils developed over grano-diorite were more erodible than those formed on basalt and sandstone.

Bryan (1968) examined the correlation coefficient between total soil loss and 22 indices of soil erodibility reported in the literature. He concluded that none of the soil indices was reliable in operation and capable of universal application, and while expressing doubt that such an index could be developed, he concluded that the percentage-weight of water stable aggregate greater than

3 mm in diameter was probably the most reliable index of soil erodibility. Farmer and Van Havern (1971) studied erosion on bare soil plots under simulated rainfall in the laboratory. They observed that the percentage of particles and aggregates between 61 and 2,000 microns and the percentage of particles and aggregates larger than 2 mm, were the most important soil variables affecting soil erosion by overland flow. The effect of the percent sand-size materials (not necessarily sand grains) was also directly related to raindrop erosion. As the proportion of sand-size material increased from 55.1 to 81.9 percent, the weight of soil eroded by raindrop splash also increased.

2.4.4 Porosity and Bulk Density

The relationship between infiltration and soil wetness has been discussed but movement through soils also depends on several properties of the soil itself. Water moves more readily through a porous soil than through a dense one, due mainly to impedance to flow in the dense soil. Adams et. al., (1958) stated that the rate at which the water moved through a profile was obviously related to soil erodibility and dependent upon the size and continuity of the channels or pores, the rate increasing with pore size. Millar et. al., (1965) also suggested that the size of the pore space in the soil may be as important as the total pore space. Bennett (1939) concluded that soils with a large volume of non-capillary pore space had a high rate of infiltration and a low susceptibility to erosion. Porosity is related to soil bulk density, a soil with low density having a high porosity (Harris, 1971).

2.4.5 Organic Matter and Soil Organisms

Soil organic matter includes all non-mineral carbon compounds found in the soil. It is the main agent responsible for black and brown colours in the soil and has profoundly beneficial effects on the soil's physical properties. It encourages granulation, makes very heavy soils easier to work by reducing plasticity and cohesion, and increases the water-holding capacity of the soil. The lack of organic matter in the soils of arid and semi-arid regions makes these very susceptible to erosion by water as well as by wind (Kohnke and Bertrand, 1959). Organic matter helps in a variety of ways, to maintain soil aggregates, such as in the formation of clay-organic complexes, by microbial mycelia and mucus, by root hairs that form a firm contact with the soil particles, and by the excreta of earthworms and micro-animals. Organic matter as plant remains can also serve as a mulch that protects the aggregates from the direct impact of raindrops. Soil humus is an important factor in the control of aeration, water-holding capacity and granulation of field soils (Millar et. al., 1965). Since most of the organic matter is found in the topsoil, any erosion that occurs will result in significant organic matter losses. The quantity of organic matter contained in soils is important from many stand points; with respect to erodibility, its greatest effect is on structure (Bennett, 1939). Within an organic matter range of 0 to 4 percent, soil erodibility tends to decrease appreciably as organic matter increases (Wischmeier, et. al., 1971).

Aggregate formation is dependent on organic matter (except in the case of cementing by iron hydroxide) and the type of bases in the soil (FAO, 1965). McCalla (1944) tested soil structure stability by the waterdrop method. A soil lump of approximately 0.15 gm (air-dry weight) was placed on a 1 mm mesh screen and waterdrops of 4.7 mm diameter, falling from a height of 30 cm at a rate of 1 drop per 4.5 seconds, were allowed to strike it. Organic compounds were tested for their influence on the stability of soil structure to water drops and the lignins, oils, fats, waxes, resin, paraffin and colloidal proteins seemed to be the most effective. Micro-organisms, particularly fungi in sufficient number and distribution, also seemed to bind the soil together. Many of the water-stable organic substances did not affect soil structure. However soil micro-organisms can rapidly transform the non-effective compounds into substances or microbial tissue effective in temporarily stabilizing the soil structure and he concluded that quantity of organic matter does not seem so important as quality in producing stability to water drops.

Erosion is influenced by the millions of organisms that inhabit the soil (Bennett, 1955; Termier and Termier, 1963). Algal, fungal and lichen populations, either alone or in association, often form surface crusts which stabilize the soil against erosion and play an important role in soil forming processes. Many sandy soils in Southern Australia possess a well-developed massive structure with water-stable aggregates extending down the profile to a depth of several feet, and such structures are associated with intense proliferation of fungal mycelia (Bond and Harris, 1964). Much of the aggregation was extremely strong and remained in the soil for a long time. Bond (1964) investigated the water repellence of sandy soils at sites in the upper south-east of South Australia by observation of infiltration patterns and measurement of contact angle of wetting. He used ring infiltrometers to assess the degree of water repellence of the soil at 60 field sites under a range of plant species and under differing farm management practices including *Pinus radiata*, heath, mallee, and *Phalaris* pasture. The infiltration rates of water when the soil at each site contained less than 1% moisture was measured and the value for contact angle of wetting estimated. The intensity of water repellence varied with species of plant cover, age of pasture and also management practices. Gilmour (1965) concluded that some hydrophobic agent associated with the ground cover was responsible for lowering infiltration. He suggested that the water could be repelled either by the litter itself or by the finely divided organic matter and associated fungal and microbial conditions at the soil-litter interface.

The activities of soil micro-organisms upon organic matter tend to develop a desirable crumb or granular structure that offers marked resistance to erosion, and favours easy penetration by plant roots and rain water (Bennett, 1955). He gave moulds as an example which sometime form entwining thread-like growths on crumbs around soil fragments, providing considerable soil stability and easy penetrability of air and water into the soil. Earthworm burrows often extend to depths of 1 or 1.5 metres or more and also serve as water channels to increase the intake of rainfall, and to facilitate the favourable internal circulation of moisture. Other groups of larger animals inhabiting the soil, namely rodents, ants, snails, spiders, mites, millipedes, centipedes and various other worms and insects have direct effects on the soil which tend to increase aeration and improve the drainage (Millar et. al., 1965). The most important group of soil fauna which affect soil structure in British agricultural soils are earthworms, for their casts, even if voided underground in the soil itself, have an excellent structure, due probably to the way soil and organic compounds are mixed together in their guts and then the mixture voided as a collection of small crumbs (Russell, 1971).

2.4.6 Stone or Coarse Particle Content

Generally, detachability of large particles decreased and that of medium and small size particles increased with a reduction in rainfall intensity. Low-intensity (7.5 cm/hour) rainfall rarely detached particles greater than 3,100 μm, whereas the high-intensity (15.5 cm/hour) rainfall detached particles as large as 5,000μm (Farmer, 1973). Raindrop impact under certain conditions could move stones as large as 10 mm diameter when they were wholly submerged in water (Ellison, 1944). Weakly (1962) reported that runoff water mainly contained small, fairly water-stable aggregates rather than textural separates, and proposed that the number of small aggregates might be a better clue to determine the erosion hazard. Chhetri (1971) also concluded that the high erodibility of Waipara soil appeared to be associated with a lower percentage of the bigger water stable aggregates greater than 2 mm in size and a high percentage of smaller water stable aggregates less than 0.25 mm. The ratio of large aggregates greater than 2 mm to mean weight diameter of the aggregate is an effective index to estimate erodibility (Yamamoto and Anderson, 1967).

2.5 RAINFALL AND SOIL-LOSS

Rainfall may act as both a detaching and a transporting force and the role played by raindrop impact in the soil erosion processes has often been emphasized (e.g. Ellison, 1944). Smith and Wischmeier (1962) suggested that study of rainfall momentum and energy in relation to erosion requires knowledge of the determining factors, that is, raindrop mass, size, size distribution, shape, velocity and direction. The effect of raindrop size and impact velocity was investigated by Bisal (1960) who found that maximum erosion will occur when the effective intensity is between 75 to 150 mm per hour, the impact velocity 7.4 meters per second. He also suggested that the height of fall for laboratory studies should not be less than 2.44 meters since the impact velocity of drops from less than this height was too low for soil detachment. Other workers have considered rainfall intensity to play a more important role in soil loss. When drop size, shape and velocity were held constant, Ekern (1950) found that the amount of sand transportation was directly proportioned to the simulated intensity. Wischmeier (1959) found that in general, maximum 30-minute intensity was more highly correlated with soil loss than maximum 5-, 15- or 60- minute intensity. Greer (1971) observed that rainfall intensity was a major factor in the erosion process. He analysed 6 years (1963-1968) of rainfall, runoff and erosion data from quarter-acre graded-row plots at the North Mississippi Branch Experiment Station in Holly Springs, Mississippi. In an experiment using artificial rainfall on variable slope plots in a green house, Neal (1938) similarly found rainfall intensity to be the most important factor affecting runoff and erosion.

After assembling and analysing all the available erosion data obtained from different erosion stations throughout the U.S.A., the U.S. Agricultural Research Service (1961) presented "A universal soil loss equation" which summarized the empirical relationships in soil loss as follows:-

$$A = RKLSCP$$

where A = the computed soil loss per unit area/yr.
R = the rainfall factor,
K = the soil erodibility factor,
L = the slope length factor,
S = the slope gradient factor,
C = the cropping management factor,
P = the erosion control practice factor.

As the rainfall factor in the universal soil-loss equation requires many years rainfall data which are usually available only in Western countries, Low (1967) tentatively put forward a method of estimating potential erosion for less developed countries where rainfall data is scant or non-existent. This equation is of the form:-

$$D = aC - b$$

where D = Specific degradation,

C = rainfall distribution coefficient,

$$= \frac{(\text{mean monthly rainfall in the wettest month})^2}{\text{mean annual rainfall}}$$

$$= \frac{p^2}{P}$$

a and b = Coefficients whose values depend upon the orographic coefficient $= \frac{\bar{H}^2}{S}$

where $\bar{H}$ = mean height of the terrain above its base-level, and

S = projected area of the terrain.

Simple methods are needed for determining the basic erodibility and runoff potential of specific soil-site complexes. There are three basic experimental approaches for determining the runoff and soil-loss from a catchment viz.

- Laboratory
- small plot
- watershed

Laboratory and small plot techniques give results comparatively quickly and cheaply compared to a watershed approach. When laboratory methods are compared with small field plots, the instrumentation, construction and maintenance of the plots are the more expensive and time-consuming. However laboratory experiments have serious limitations in that the natural condition of the field plot soil cannot be exactly duplicated in the laboratory, and the creation of artificial rain, which is comparable to natural rainfall in the field, is complicated and needs very accurate measurement.

In field experiments in the Lower Cotter Catchment area Gilmour (1965) used 5.6 square metres permanent plots to measure surface runoff and soil loss for each natural rainfall over a year within a range of soil-vegetation types. He found that native eucalypt forests and well established pine plantations provided excellent catchment protection on all soil types. Young pine plantations on soil types with restricted drainage in the subsoil provided insufficient protection and most of the soil loss measured originated on very bare areas such as firebreaks. In contrast, Hayward (1969) found that the runoff plot method was totally unsuitable for erosion research in the South Island hill and high country of New Zealand where he used 4 square metres plots in the Rakaia catchment, representing drier sub-alpine/alpine Canterbury high country, to determine the extent of soil movement within a mountain catchment and to assess the influence of plant cover and type on soil stability.

The use of spraying devices to apply water drops as simulated rain in the study of runoff and erosion started in the early 1930's (Lowdermilk, 1930; Duleys and Hays, 1932; Nichols and Sexton, 1932; Hendrickson, 1934). A rainfall simulator that applied water drops uniformly on three or four field plots simultaneously was developed by Meyer and McCune (1958). Smaller laboratory scale simulators and drop towers have been frequently used (Mihara, 1952; Basu and Puranik, 1954; Adams et. al., 1957; Rose, 1960, 1961; Bisal, 1960; Mutchler and Moldenhauer, 1963; Chow and Harbaugh, 1965; Turner, 1965; Balci, 1968; Chhetri, 1971; Farmer, 1973).

In general two types of rainfall simulation or application have been used -

- Spray Nozzle Types
- Dripping Types .

Laws (1940) and Laws and Parsons (1943) used a spray nozzle system in an attempt to reproduce drop-size distribution and velocity of impact of natural rainfall. Meyer and McCune (1958) developed a spray nozzle simulator (called a "rainulator") which adequately simulated rainfall with respect to drop size distribution and velocity of impact. The spray nozzle type rainfall simulator has been frequently used in experimental work in the U.S.A., and to a lesser extent in Australia (Gilmour, 1965; Turner, 1965; and Turner and Langford, 1969).

The dripping type of rainfall simulator has been extensively used for small scale laboratory studies of soil-loss. The dripping mechanisms have varied widely from hanging yarns of cotton, nylon or wool (e.g. Chhetri, 1971), to tubes ranging from a single tube, to a combination of different size tubes or hypodermic needles made in the form of a telescope (e.g. Kinnell, 1974). Further dripping types of simulators have been described by Ellison and Pomerence (1944), Ekern and Muckenhirn (1947), Woodburn (1948), Bisal (1950, 1960), Basu and Puranik (1954), Adams et. al.,(1957), Rose (1960), Mutchler and Moldenhauer (1963), Chow and Harbaugh (1965) and Balci (1968).

Smith and Wischmeier (1962) pointed out that devices used to apply water drops as simulated rain for the study of runoff and erosion had one common weakness - either drop size or velocity or both were appreciably lower than in natural rainfall of medium to high intensity. If the soil loss under rainfall simulation is studied in the laboratory the preparation of the sample bed could probably have a significant effect on the soil loss measured. It is suggested that this has not been given sufficient attention in the studies reported but in any event laboratory studies could only give an index of erodibility because it is not practicable to obtain undisturbed soil samples for the laboratory tests.

Bryan (1968) stated that soil erodibility may be assessed either by actual measurements of soil-loss under controlled conditions (e.g. as in rainfall simulation), or by the isolation of certain soil properties as indices of erodibility. Measurement of soil-loss under controlled conditions in the field requires elaborate installations and observation for lengthy periods. Indices of erodibility, on the other hand, can usually be derived from normal analytical data and therefore require little special equipment. Wischmeier and Mannering (1969) investigated the relation between infiltration capacity and capacity to resist detachment and transportation by rainfall and runoff and soil physical and chemical properties, in a 5-year field, laboratory and statistical study including 55 selected corn belt soils of Indiana, Georgia and Minnesota. They derived an empirical equation including an erodibility factor for specific soils. From several tests, they found that the equation appeared to predict with good accuracy the numerical erodibility index for any specific soil in the silt, silt-loam, loam or sandy loam texture groups. These are the most erodible.

In an effort to compare the effectiveness of different methods for assessing soil erodibility, Chhetri (1971) measured soil-loss from a prepared soil-bed under simulated rainfall in the laboratory. About 6 cu. metres of top half metre of the surface soil was collected from the field, air dried and made into a soil bed (2.7 m x 0.9 m x 0.3 m) after passing through an 8 mm square-hole sieve. At the bottom of the soil-bed a layer of gravel was glued. Then a mixture of small gravel and sand was spread over it to 5 cm depth. The soil-bed was filled in three layers from one end to the other without reversing the direction. Soil was filled up to 5 cm below the top edges of the soil-bed and a light wooden plank used to level the soil surface, and no more compaction other than that which naturally occurred during the process of filling was attempted while levelling the soil surface. He used the soil-loss as a standard with which to compare readily measurable properties of soil, reported by previous workers to be indices of erodibility. He also applied measured properties of soil to the soil erodibility equation developed by Wischmeier and Mannering (1969) and found that the results were the same as when actually measured under simulated rainfall erosion tests, thus supporting the validity of measurable soil properties as indices of erodibility, as suggested by Hayward (1969).

2.6 FOREST MANAGEMENT PRACTICES AND SOIL EROSION

Forests are very effective in controlling erosion, especially if they are undisturbed. The tree canopy intercepts rainfall and reduces its energy. Drops that reach the ground are quickly absorbed in the leaf litter and from there into the highly porous soil surface. However, when forest is disturbed by trampling of livestock or by logging operations, the natural protection from erosion may be impaired or destroyed.

Natural erosion processes operate in all forests especially during periods of heavy rainfall. Major factors in soil erosion are improper cultivation methods and mismanagement of tree and herbaceous vegetation which leave the soil stripped of protection and susceptible to the erosive agencies of wind and water (Brown et.al., 1968). Thus forests control erosion effectively only if they are properly managed (Kohnke and Bertrand, 1959).

Combinations of tree and grass, as well as combinations of trees and shrubs, have important applications for the control of runoff and erosion in special conditions (Bennett, 1939). In a well-stocked stand the tree tops are usually close enough to touch and form a closed canopy and frequently small trees, shrubs and other forms of lesser vegetation make up a layer of undergrowth of varying thickness which also provides protection against excessive run-off and soil erosion.

2.6.1 The Importance of Soil Cover

Vegetative cover is the best practical protection against excessive sheet erosion because it breaks raindrop impact and favourably influences infiltration capacity. The floors of forests are often covered with a thick carpet of litter and the underlying soil is kept open and granular, providing ideal conditions for absorption of water and rainfall is stored and run-off more gradual.

Osborn (1956) studied the effects of vegetative cover and soil on splash-erosion on rangeland in Texas and Okalahoma and developed vegetative cover requirements to control splash-erosion on soils with various textures and plant species composition. Water erosion hazard varied with soil detachability and for equal protection, 5600 kilograms of cover per hectare were required for a soil with a very high detachability index of 90 percent (as compared to a standard structureless sand as 100 percent), and, at the other extreme, a soil with a detachability index of 10 percent required only about 1700 kg/ha of cover.

On the basis of simulated rain experiments on granite soils in southern Idaho, Packer (1951) concluded that adequate control of summer storm run-off and erosion on wheatgrass (Agropyron inerma) range requires at least 70 percent gound cover of plants and litter and that bare openings should be no larger than 10 cm in diameter. On cheatgrass (Boramus tectorum) range, 70 percent ground cover is again required but bare openings should be no larger than 6 centimeters. Packer (1963) also prescribed ground cover density of at least 70 percent and soil bulk densities not greater than 1.04 g/cc as necessary to maintain soil stability on the Gallatin elk winter range in south-central Montana.

Using a rainfall simulator on a subalpine cattle range in central Utah, Meeuwig (1965) found that soil erosion was more closely correlated with the proportion of soil surface protected from direct raindrop impact by plants, litter and stone than any other measured variable. In a later study Meeuwig (1970) applied simulated rain to small plots on seven mountain rangeland sites in Utah, Idaho and Mpntana, and again found that the magnitude of erosion depended primarily on the proportion of the soil surface protected from direct raindrop impact by plants, litter and (in some cases) stone.

Forests do not always intercept the entire precipitation in a storm event and transfer it to soil run-off. For example where the precipitation is particularly heavy, as in the slopes of the Assam mountains in India where the average yearly precipitation amounts to 12,500 mm and sometimes reaches more than 1,000 mm in 24 hours. However when the precipitation is lower and distributed more evenly over the year, forests may prevent surface run-off almost completely. The peak of water discharge on forested terrain seldom exceeds rates of the order of 600 $m^3/sec/km^2$, whereas on eroded and bare areas it may reach 1000 $m^3/sec/km^2$ or more (Molchanov, 1960). He gave an example from the Mississippi region of the United States of America where in a single flood lasting from 15 December 1936 to 25 February 1937, 62% of rainfall became run-off from the surface of agricultural land, causing erosion of 85 tonne/ha of soil. Over a longer period this run-off reached even 75-96%. Under the same conditions, a low oak stand would have absorbed in the soil as much as 98% of the precipitation leaving only 2% to run off the surface, showing that even a young stand of oak is a valuable protection against erosion.

The reduction in surface run-off by forest cover as compared to grass is particularly important during periods of excessive rainfall since surface run-off is primarily responsible for erosion and for flooding following a rapid rise in stream levels (Leyton, 1962). Removal of natural vegetation (by spraying with Grammoxone) increased run-off from 7 to 21% of the annual rainfall, while soil on plots carrying a vegetal cover showed 40-50% higher infiltration rates than bare soil (loess) (Tadmor and Shanan, 1969). The amount of ground cover was shown to be more important than the type of cover in controlling soil loss and surface run-off in the Cotter catchment of the Australian Capital Territory. Soil loss was negligible from plots with more than 0.72 kg/m^2 of ground cover, but marked increases in soil loss resulted from cover reductions below this value and a highly significant correlation was obtained between the constant infiltration rate in the 'wet run' of the experiments and the oven dry weight of ground cover (Gilmour, 1965). Thistlethwaite (1970) used the same plot design as that developed by Gilmour (1965) to investigate surface run-off effects in P. radiata plantations in the Lower Cotter Catchment. The linear regressions of total ground cover (weight of dry matter per unit area) and surface run-off were highly significant, the relationships being primarily due to the presence of the F layer. Thistlethwaite concluded that in P. radiata plantation if the infiltration component is neglected, the run-off decreases as the ground cover, and particularly the mass of decomposing pine litter, increases.

2.6.2 Timber Utilization and Silvicultural Treatments

The forest services of Australia are responsible for managing large areas of native forest. About 141,700 hectares of these forests are exploited annually - 99.5 percent of the cut is from forests in the States and the remaining 0.5 percent is from forests in the Territories administrated by the Commonwealth (Brown et. al., 1968). The main objective of management of the native forest in Australia is timber production. The productivity of the indigenous species is usually very low, and intensive management to achieve maximum production of these species is probably justified on only a small part of the forests (Florence, 1969).

The most important silvicultural systems adopted in Australia are:-

- Clear-cutting, for example in most plantations;
- Seed-trees,for example in rain forests of Queensland;
- Selection, for example New South Wales coastal eucalypts and Cypress areas of Queensland;
- Coppice.

The silvicultural systems have markedly different effects in terms of localized erosion.

More than a century ago Sir Charles Lyell (1849) commented on the increased sediment loads carried by streams in the eastern United States as a result of forest clearing. Packer (1967) summarised research work to determine the effects on erosion of forest treatments associated with timber harvesting and concluded that:-

- Undisturbed forests produce only small amounts of sediment and a streamflow usually suitable for drinking;
- Timber cutting does not adversely affect water quality, with the possible exception of substantial increases in streambank erosion caused by higher streamflow peaks;
- Logging, or skidding of logs from forests, can sometimes increase sedimentation considerably, depending upon the location and drainage of skidways, the erodibility and stoniness of soils, and the rapidity of re-vegetation of skidways;
- Roads that are inadequately drained or are located too close to streams are the main cause of deterioration of water quality in forests.

Bormann and Likens (1970) reported that when all vegetation was cut in a 15.6 hectares watershed experimental forest in New Hampshire, deforestation had a pronounced effect on run-off, with an increase in the amount and flow rate of water and the breakdown of biological barriers to erosion and transportation. Anderson (1971) reported some effects of forest management practices on erosion. Past land use, forest fires, road building, poor logging and conversion of steep lands to grass-land had increased sediment discharge by factors ranging from 1.24 to more than 4. Major floods have increased subsequent turbidity of streamflow by a factor of 2, and increases were greater in logged areas than in undisturbed watersheds. Most landslides were associated with road development, some with logged areas, and very few with undisturbed forest areas. Barton (1972) discussed the desirability of forestry practice within a developed water catchment in the Hunva ranges, New Zealand. Removal of at least 20 percent of the vegetation from an area increased water yield, and the chief cause of water pollution from logging operations was increased sedimentation from erosion caused not by the felling of the vegetation, but by the mechanized methods employed to remove the timber.

Although fire may be a major cause of erosion from forested catchments, Boughton (1970) considered there are three other principal sources of turbidity and erosion problems due to forestry practices and activities in Australia. These are:-

- Construction of roads through forests for general access, for fire control purposes, and for the extraction of timber;
- Logging activities, particularly where work is carried out around water courses or where skid tracks are used to haul logs to loading areas;
- Clearing of large areas of native forest for the establishment of a plantation.

Construction of roads involves the removal of plant and litter protection over a wide tract of forest to expose raw mineral soil, and thus effect the soil porosity and permeability. Lull (1962) stated that generally, with mechanized logging, soil compaction due to the movement of equipment may occur over up to 40% of an area while the skid roads take up to 20%. Fredriksen (1965) observed run-off from the first rainstorms after road construction removed 250 times the concentration of sediment carried in an adjacent undisturbed stream. Dyrness (1967a) reported that in one drainage in western Oregon, 72 percent of the mass soil erosion events resulting from a major flood were in some way associated with logging roads. Swanston (1971) stated that logging, road building and fire play an important part in the initiation and acceleration of soil mass movement. Road building was the most damaging activity with soil failures resulting largely from slope loading, back-slope cutting and inadequate slope drainage. Logging and fire affect soil stability primarily through destruction of natural mechanical support of the soils, removal of surface cover and obstruction of main drainage channels by debris. In two steep headwater drainages, H.J. Andrews Experimental Forest, Oregon, landslides were the predominant source of increased sedimentation of streams over a 9 year period following timber harvest, (Fredriksen, 1970). At a forest hydrological research site, North Queensland, the bulk of the suspended sediment in streams was frequently derived from a small number of sediment source areas such as poorly located roads, snig tracks and log ramps (Queensland Dept. of Forestry, 1971).

Megahan and Kidd (1972) used erosion plots and sediment dams to evaluate the effect of jammer and skyline logging systems on erosion and sedimentation in steep, ephemeral drainages in the Idaho Batholith of Central Idaho. Five years of plot data indicated no difference in erosion resulting from the two skidding systems as applied in the study, but sediment dam data showed the logging operation alone (that is excluding roads) increased sediment production by a factor of about 0.6 over the natural sediment rate. Roads associated with the jammer logging system increased sediment production on an average about 750 times the natural rate for the six-year period following construction.

Fire may be a serious factor in accelerating the erosion processes in forested catchments. They cause a marked change in the micro-environment and upset the natural balance. Severe fires or a succession of relatively light fires can result in an increased rate of run-off causing soil erosion, the flooding of rivers and the silting of water reservoirs. Some tentative studies of fire effects on vegetation and soils were made by Universities and Forest Services before 1954 and fire control research on a national basis began in Australia in 1954 with the establishment within the Commonwealth Forestry and Timber Bureau of a bush fire research section. Now much of the work on fire effects is carried out by forestry research groups, plant physiologists and ecologists, Zoologists, soil scientists and hydrologists working within the Universities, C.S.I.R.O. and Conservation Authorities (Kellow, 1969).

Forest fires are of two types, uncontrolled or wild fires and controlled or prescribed burns and both are often followed by increased rates of surface erosion. Although severe burning may cause increased erodibility, light burning apparently has little effect on soil properties. A change of primary importance caused by fire is removal of protective cover of vegetation and litter. Since organic matter is an important cementing agent in soil aggregate formation, any removal by fire may have an adverse effect on structural stability of the soil. Intensive burning increases erosion and run-off and the amount of run-off and erosion following any burning also depends on the timing and pattern of rainfall which follow (Dyrness, 1967b). Boughton (1970) contrasts the increase in stream-flow and erosion from a heavy storm which occurred seven months after a fire at Wallace's Creek in the Australian Alps with the Chichester Catchment near Newcastle with no heavy rain experienced six months after the fire. Sediment concentrations at Wallace's Creek were about one thousand times those found before the fire, whereas there was no erosion and increased in turbidity in the Chichester Catchment.

The use of low intensity prescribed burning as a silvicultural tool and a means of removing excessive amounts of dry fuel from the floor of the forest to reduce high intensity wildfires has increased in Australia over the last decade. Gilmour and Cheney (1968) measured infiltration rates before and after a prescribed burn of low intensity in a 23-year old plantation of radiata pine (Pinus radiata D. Don) at Stromlo Forest, A.C.T. by applying artificial rainfall, at a rate of 80 points in 15 minutes, to run-off plots which were 5.6 square metres in area. They concluded that a prescribed burn of low intensity could be carried out in a plantation of radiata pine without causing either soil loss or a significant reduction in infiltration. The fire reduced the average fuel quantity on the plots from 8.8 t/ha to 6.3 t/ha and greatly reduced the fire hazard by removing the in-flammable fire fuels and the heavy slash piles. The weight of ground cover left after the fire in the study was close to 7.2 t/ha which would be sufficient to keep surface run-off and soil loss at a minimum in both native forests and pine plantations (Gilmour, 1965).

Brown and Krygier (1971) studied the impact of road construction, two patterns of clear-cut logging, and control slash burning on the suspended sediment yield and concentration from three small watersheds in the Oregon Coast Range for 11 years. Sediment production was double after road construction but before logging in one watershed, and was tripled after burning and clear-cutting of another watershed. Mersereau and Dyrness (1972) also reported that clearcut logging and slash burning in a steep 96 hectare watershed in Western Oregon resulted in increased rates of soil movement, especially on slopes unprotected by organic debris. During the first growing season after burning, soil movement, which largely occurred as dry gravel, was more pronounced on 80% than 60% slopes, on south aspects compared with north aspects, and in areas having little plant cover compared with well vegetated areas. By the second growing season after burning, rapid invasion by vegetation essentially halted soil movement on all slopes except extremely stony talus areas. Craig (1969), from his own results together with those of nearly all other workers who have done similar studies, concluded that heating or burning a soil even at quite high temperatures, causes very little breakdown in structure, but leads to the production of soil aggregates which are much more stable to raindrop impact than the original unburnt ones.

2.6.3 Afforestation and Reforestation

In water supply catchments, clearing of native vegetation for planting of exotic softwood forests (usually radiata pine) has produced problems of turbidity. A period of two to three years occurs from the time clearing of the native vegetation until the plantation trees grow enough to establish an erosion retarding cover (Boughton, 1970). Hamilton (1964) studied the changes produced in the forest floor and soil profile characteristics, when communities dominated by eucalypts are replaced by forests of radiata pine. He concluded that important changes in soil properties which occur under pines, such as increase in bulk density and decrease in organic matter, suggest declining suitability for plant growth.

Ursic and Duffy (1972) examined the run-off and sediment yield characteristics of eight small, pine-covered watersheds, with a wide range of soil and antecedent erosion conditions. Southern pines, particularly loblolly (*Pinus taeda* L.) were ideal for erosion control, and average annual water and sediment yields could be satisfactorily predicted from annual precipitation and soil survey information. They also discussed the efficiency of pine plantings, in controlling flood flow and sediment yields.

2.6.4 Effects of Soil Conservation Practices

Proper land use for perpetual benefit can only be achieved through soil conservation, that is, if the land is properly managed under suitable conditions of vegetation. Ogihara (1960) in Japan, recognised that although forest is almost absolutely effective against surface erosion, it is non-effective against deep erosion.

The Standing Committee on Soil Conservation (1971) reported, when the soil conservation organizations were first established in

Australia and commenced tackling the widespread problems of soil erosion and declining fertility, that there were many opportunities to demonstrate the more economic production achieved by soil conservation practices and land use. The application of soil conservation measures reversed the pattern of declining yields and opened the way for the improvement of soil resources. The benefits of soil conservation practices and land use for farm lands are:-

- continued production with increasing yields;
- increased production financed from annual returns; and
- increased protection of a reservoir for a relatively low cost.

Sediment production resulting from surface erosion on fill slopes can be reduced more than 95% by application of grass seed and fertilizer, and protecting the soil with straw mulch and wire netting (Bethlahmy and Kidd, 1965). A number of non-forest-related activities such as powerline clearing, dam construction and strip mining are also sources of sediment from lands within the forests. The same principles as for road construction and logging should be applied so that bare soil is kept to a minimum and stabilized by vegetation.

2.7 GENERAL CONCLUSION

Soil erosion is the result of incorrect land use. Severity of soil erosion at any place depends upon the effects and interaction of climate, topography, vegetation, soil and human factors. Some soils erode easily while others resist the action of erosive agents under similar environment because of different physical, chemical and biological properties.

Soil properties important in relation to water erosion are those properties that affect the infiltration rate and which resist dispersion during rainfall and run-off. Except for very sandy soils, detachment and transportation are essential components of soil erosion and the rate of erosion is inversely proportional to the resistance to detachment and transportation of soil particles.

Soil erodibility may be assessed either by actual measurement of soil-loss under controlled conditions, or by the isolation of certain soil properties as indices of erodibility. The important soil properties investigated and measured as indices of erodibility are dispersion ratio, clay ratio, aggregate stability, porosity and bulk density, organic matter content and particle size distribution of the soil.

It is generally recognised that soils developed under forest possess a higher infiltration capacity and promote downward movement of rainfall into the soil because of litter, humus layers and the presence of old root channels. Forest vegetation minimizes soil erosion largely by the effect of plant crowns and litter in eliminating the destructive physical effects of raindrops impacting soil. Without this protection, soil aggregates are broken down and infiltration rates decrease resulting in surface run-off and erosion.

Timber utilization, cultural treatments, reforestation, fire, the construction of access roads and tracks in connection with the protection and production of the forests are important aspects of forestry practices which affect the soil erosion. Although there is no control over the slow processes of geologic erosion, which occurs naturally due to the climate, topography, vegetative cover, soil and geology of the area, there are remedies for any forest management activity that disturbs the natural vegetative cover, the existing drainage pattern and the soil stability and thus tend to cause "accelerated erosion".

CHAPTER 3

MATERIALS AND METHODS

3.1 INTRODUCTION

Long term studies are very desirable in assessing the erodibility of soils but were not practicable in connection with this thesis and a diverse area with a long history was selected for detailed study. The study area is along a three kilometres section of the Bendora gravity main in the Lower Cotter Catchment of the Australian Capital Territory. It passes through pine and eucalypt forest growing on soils of shale and granite origin. The selected area has a range of slopes and parent materials and in part has been reforested with pine over a period of time. Within the study there are areas that had been eroded and areas where past erosion has been modified by revegetation. The location of the study area is shown in Fig. 3.1.

Under each forest type soil parameters shown by other workers to be indices of erodibility, were measured. The indices measured and reviewed in section 2.4, were dispersion ratio, clay ratio, aggregate stability, organic matter content, particle size distribution, porosity and bulk density. Other soil parameters, namely penetration, soil colour, soil reaction (pH), total nitrogen and phosphorus, total cations (Ca, Mg, K, Na, Fe, Mn, Zn), soil moisture at $\frac{1}{3}$ BAR (field capacity) and 15 BAR (Wilting point) and vegetative cover, forest floor litter and soil organisms were also measured.

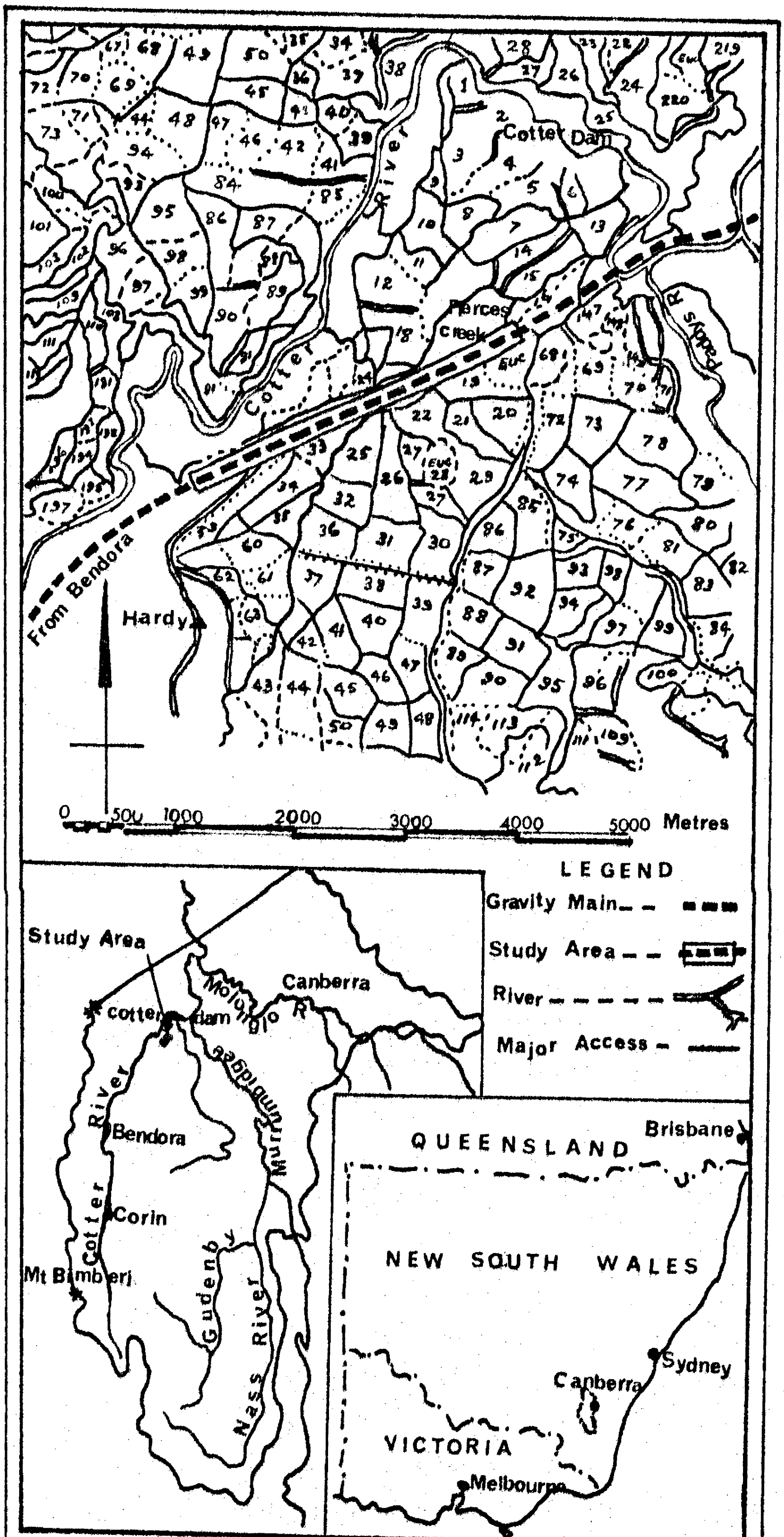

FIGURE 3.1 Location Map of Study Area

3.2 THE STUDY AREA

3.2.1 Topography

The Bendora gravity water main in the Lower Cotter Catchment passes through dry sclerophyll forest in hilly terrain for most of its length in the reservoir catchment, and also through the Pierces Creek pine plantation.

The slopes in this area are gentle to moderately steep. The terrain is gentle to moderately undulating in the lower reaches where the study area was selected. Although altitude ranges within the catchment from 510 m at the Cotter dam to 1912 m at Mt Bimberi, the study area is between 610–640 m above sea level.

3.2.2 Climate

Regional climatic records are available in a survey of the climate of Canberra and the Australian Capital Territory (Bureau of Meterology, 1968). The climate of the Cotter catchment itself is described by Resource & Environment Consultant Group (1973) and includes an isohyetal map.

Rainfall is generally more reliable in the winter and spring but there is little monthly variation. The rainfall figures for Pierces Creek Forestry Settlement which is about three kilometres from the farthest end of the study area, show the mean annual rainfall 71.6 cm, the average number of days of rain per month 6–12 days, the driest month February (5.3 cm) and the wettest, October (8.5 cm). Temperature figures are not available for Pierces Creek but the average figures for the last five years before sampling, that is between 1967–1971, at Uriarra Forest the nearest station to the study area, shows the highest screen maximum as 36.9^{o}C, the lowest screen maximum 5.4^{o}C and the lowest screen minimum -4.8^{o}C.

3.2.3 Geology

The geology of the Cotter valley influences:

(i) the physiography of the valley;

(ii) the soil fertility and growth of indigenous and exotic plants; and

(iii) soil and slope stability and therefore water quality (Stevens, 1973).

There are three main types of geological formations in the lower Cotter catchment (Thistlethwaite, 1970):-

- granite, granodiorite, granite porphyry, (igneous Upper Silurian to Devonian);
- phyllite, sandstone, slate, chert, quartzite, greywacke (sediments and metamorphosed sediments, Ordovician);
- acid tuff, pyroxene, dacite, calcareous shale (volcanics and metamorphosed sediments, Upper to Mid-Silurian).

The area under study falls within the boundaries of Shanmono Flat Granodiorite, which is part of the Murrumbidgee batholith of Silurian-Devonian times (Noakes, 1954).

3.2.4 Soils

Pryor (1939) recorded three main groups of soils in the Cotter catchment -

- red-yellow podzolics,
- red forest loams, and
- alpine humus

Podzolics occur at elevations below about 900 m, red forest loams on sheltered aspects up to about 1200 m, and alpine humus at high basins and gentle slopes mostly near the crest of the Brindabella Range. Below about 1050 m in most of the A.C.T., normal (medial), maximal and minimal red and yellow podzolic soils are found on gentle topography which allows fullest expression of the mature profiles (Pryor and Brewer, 1954). The Atlas of Australian Soils (C.S.I.R.O., 1966) shows four mapping units occupying various parts of the Cotter catchment. Stevens (1973) in discussing the soils of the Cotter catchment described the following -

- the general types of soils present in the catchment;
- the places they most commonly occur;
- the effect of geology and topography on soil distribution;
- some soil-plant interactions; and
- some soil-management interactions.

3.2.5 Vegetation

Within the study area, the natural eucalypt stands are of low quality and dominated mainly by red stringybark (*E. macrorhyncha*), brittle gum (*E. mannifera*) and scribbly gum (*E. rossii*) associations. Tree boles are of poor form and are quite unevenly-spaced, forming a stunted type of dry sclerophyll forest. The Monterey pine (*Pinus radiata*) plantations are 39-40 years old.

A sparse covering of grasses, small shrubs and ground herbs has developed under eucalypts. In most of the pine plots, natural pine seedlings have developed (Plate 4.5, 4.6). The pipeline bench and all areas where vegetation was disturbed during construction, have been seeded and fertilised (Fitzgerald, 1972) so that at the time of study, the gravity main pipeline cutting in the study area was well covered with grasses, clovers, herbs and shrubs (Plate 4.11). Natural pine seedlings are encroaching on the pipeline cuttings along the edge of the plantation in some areas.

3.2.6 History

In 1926 exotic pine establishment was initiated as a protective measure on 1214 hectares of land near the Cotter Dam in the Lower Cotter Catchment. This afforestation program was completed by 1930, and reafforestation then commenced. Plantation establishment in the Cotter catchment ceased in 1964. The plantation area (4856 ha) represents ten percent of the Cotter catchment area (Thistlethwaite, 1970).

The Bendora Water Main, which is an underground 137-152 cm diameter main, was constructed from the Bendora Dam approximately parallel to the Cotter River for about eighteeen kilometres. Construction commenced in 1966 and continued to 1968. In the design and construction of this main special attention was given to stabilisation of the ground surfaces and minimising erosion both during construction and thereafter (Dept. of Works, 1966). Harvey (1972) has described the contract provisions. The Contractor was allowed to cut down trees and clear brush for operating space up to seven metres uphill of the centre line and five metres downhill, a total width of twelve metres. The pipeline bench has regularly spaced grassed cross drains and all areas where vegetation was disturbed during construction have been seeded and fertilised. Abandoned borrow pits have been contoured and seeded and steep batters have been stabilised with emulsion and seeded. The bench was reseeded and fertilised by aerial spraying during two successive years.

3.3 SITE SELECTION

The aim of this study was to assess the effects of change from one form of land use to another on soil properties related to erosion. The Bendora gravity main passes through Pierces Creek pine plantation for about two kilometres and presented a situation in which erosion and land use change from forestry operations and engineering construction could be studied. A section of the gravity main (about three kilometres in length) where it passed through granite and shale soils near the Pierces Creek Settlement was selected. Within this length seven sites were selected on the basis of differences in geology, slope and vegetation (Plate 3.1).

PLATE 3.1 Location of Sites
(Based on Civil Aerial Survey Photo No. 8740)

1 -	Granite -	Eucalypt -	Shallow Slope -	GE 2
2 -	" -	" -	Steep " -	GE 1
3 -	" -	Pine -	Shallow " -	GP 2
4 -	" -	" -	Steep " -	GP 1
5 -	Shale -	" -	Shallow " -	SP 2
6 -	" -	" -	Steep " -	SP 1
7 -	" -	Eucalypt -	" " -	SE 1

Scale: 1cm = 250 metres

TABLE 3.1 Descriptions of Sites

No.	Soil	Vegetation	Slope	Site Notation
1	Granite	Eucalypt	shallow $< 13^{\circ} > 8^{\circ}$	GE2
2	"	"	steep $> 16^{\circ} < 21^{\circ}$	GE1
3	"	Pine	shallow $< 10^{\circ} > 5^{\circ}$	GP2
4	"	"	steep $> 23^{\circ} < 29^{\circ}$	GP1
5	Shale	"	shallow $< 16^{\circ} > 13^{\circ}$	SP2
6	"	"	steep $> 25^{\circ} < 30^{\circ}$	SP1
7	"	Eucalypt	steep $> 20^{\circ} < 25^{\circ}$	SE1

3.4 SELECTION OF PLOTS

Three plots were located across the gravity main at each site, one above the gravity main, one on the revegetated area of the gravity main and the other below the gravity main. Downslope plots were selected to avoid any trace of destruction by engineering works, such as topping with earth from the gravity main. All plots were 50 square metres (25 m x 2 m) in size.

Figure 3.2 and 3.3 show the location, size and the pattern of sampling of the plots at each site. General descriptions of the plots are given in Appendix II.

3.5 NOTATION

The following system of notation was adopted for ease and accuracy in field work.

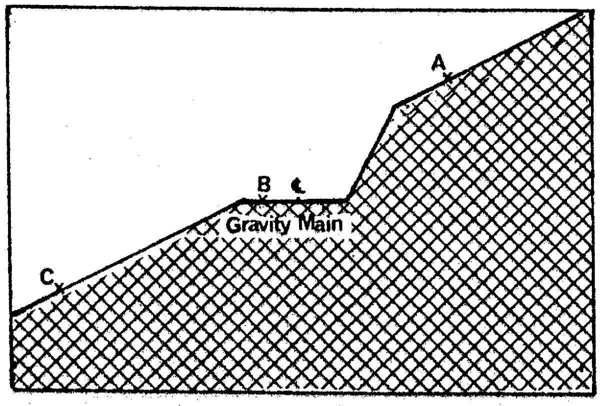

FIGURE 3.2 Location of Plots

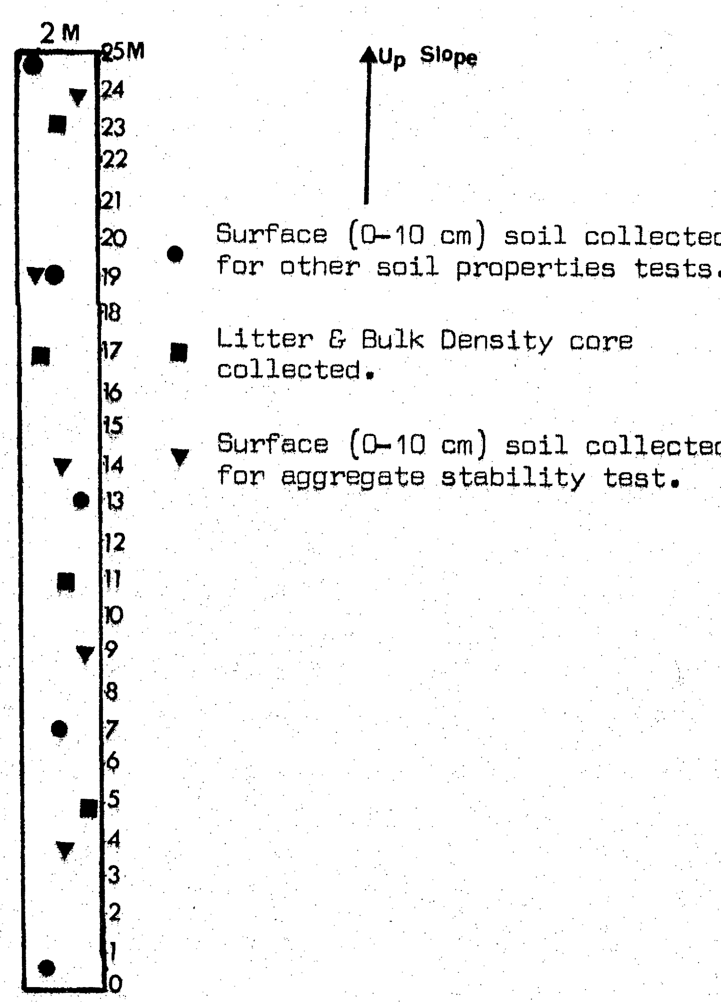

FIGURE 3.3 Field Sampling Pattern

3.5.1 Plots

G	denotes	granite origin
S	"	shale origin
E	"	eucalypt forests
P	"	pine plantation
1	"	steep slope
2	"	shallow slope
A	"	the position above the gravity main pipeline along the slope.
B	"	the position on the gravity main revegetation
C	"	the position below the gravity main.

3.5.2 Samples

l	denotes	litter
fh	"	fermentation/humus
ss	"	surface soil samples (0–10 cm) for other soil properties tests.
st	"	surface soil samples (0–10 cm) for soil aggregate stability test.
bd	"	bulk density samples.
1,2,3,4,5	"	No. of samples, starting from downslope to upslope.

Example GE1Ass$_1$ denotes surface soil sample No. 1, collected for other soil properties tests, from the plot above the gravity main, under eucalypt forest, steep slope on granite origin.

3.6 SAMPLING

A systematic sampling pattern (Fig. 3.3) was used for each plot.

3.6.1 Vegetation

The Point Height Intercepts method was used in determining cover density. Two '30' metres tapes were laid out two metres apart and parallel to each other along the longer boundaries of the plot. The following information was recorded vertically below and above each half metre point. Whether bare rock, bare soil, leaf litter, bark litter, branches, grass or other matter were present directly below the tape, and whether there was clear sky or canopy cover vertically above the same mark. The one hundred points (2 x 25 x 2) were used to calculate the percentage cover density for the canopy and the ground for each plot.

3.6.2 Forest Litter

Four samples (Fig. 3.3) of litter from the forest-floor were collected in each plot. A square steel frame with an area of 1/16 m^2 (25 cm x 25 cm) was pressed into the litter, and a sharp knife used to cut the litter around the perimeter of the frame. All the litter within the frame was removed down to the mineral soil, placed in a labelled plastic bag and returned to the laboratory.

3.6.3 Mineral Soil

Four samples for bulk density, five samples for other soil properties tests, and five samples for the soil aggregate stability test, were collected in each plot.

The collection of bulk density samples in the field was done using a steel bulk density corer (10 cm x 10 cm x 15 cm). The corer was driven into the ground with minimum disturbance using a hammer and wooden block where the forest litter had been collected. At every B plot (i.e. on the gravity main revegetated area) the corer was driven down only 7.5 cm. The corer was dug from the ground using a trowel, and surplus soil trimmed from the ends of the core by means of a sharp knife. The soil cores were extruded into labelled thick brown paper bags, and transported to the laboratory.

Surface (0-10 cm) soil samples for the soil property test were collected at each plot position by using the soil corer. The composite sample was placed in a labelled thick brown paper bag and taken immediately to the laboratory.

Surface (0-10 cm) soil samples for the soil aggregate stability test were collected at each plot position by using the same corer. The composite sample was placed in a separate labelled thick brown paper bag and taken immediately to the laboratory.

3.6.4 Penetration

A 'Pocket Penetrometer' was used for a penetration test at each plot. By walking diagonally along the plot, twenty replicates were taken and the mean value of penetration (Kg/cm^2) for each plot was calculated.

3.6.5 Physiography

For each plot:-

- Aspect was measured to the nearest degree by taking a bearing with a prismatic compass;
- Slope steepness was measured by using an Abney level;
- Slope shape was assessed as concave, linear or convex.

3.7 ANALYTICAL PROCEDURE

3.7.1 Bulk Density

For the definition of bulk density and other soil vocabulary refer Appendix I.

At all 'A' and 'C' plots the bulk density cores were 1500 cc (10 cm x 10 cm x 15 cm) while at all 'B' plots, that is those on the gravity main revegetated area, the cores were 750 cc (10 cm x 10 cm x 7.5 cm). The soil bulk cores were weighed immediately after return from the field, oven-dried at 105^{o}C for 24 hours and the oven-dry weight determined. The field-moisture content was calculated and the bulk density expressed in grams per cubic centimeter of soil. The values for the four cores extracted at each plot were used to determine the mean value.

3.7.2 Total Porosity and Non-Capillary Porosity

Total Porosity (%) was calculated by the formula,

$$\text{Total Porosity (\%)} = 100 - \frac{(B\,D \times 100)}{P\,D}$$

where B D = Bulk Density - g/cc

P D = Particle Density - g/cc.

The particle density (the density of the soil particles collectively, expressed as the ratio of the total mass of solid particles to their volume in g/cc) was determined in the laboratory for each soil bulk sample and the respective total porosity was calculated with the corresponding bulk density.

The coarse particles vary due to stone content from site to site; the particles greater than 2 mm in diameter were therefore removed from each of the bulk density samples by sieving. Bulk density of the soil alone was then calculated by subtracting the known weight and calculated volume of coarse particles from the weight and volume of the original sample. Capillary porosity was then calculated.

$$\text{Capillary Porosity (\%)} = \frac{\text{Wt. of water held in soil at field capacity}}{\text{Wt. of oven dry soil}} \times \begin{array}{c}\text{Bulk}\\ \text{Density}\\ \text{(soil alone)}\end{array}$$

Non-Capillary porosity is calculated by subracting capillary porosity from total porosity.

3.7.3 Coarse Particles

Air-dried soil samples were sieved on a 2 mm mesh sieve to separate the coarse particles from the fine earth. The percentage of soil material over 2 mm (coarse particle) was calculated by weighing after organic matter such as roots and charcoal had been removed. The coarse particle was discarded after weighing, while fine earth was kept for determination of other soil properties.

3.7.4 Soil Colour

The Munsell (U.S.D.A. Misc. Pub. 425) book of soil colour chips was used to determine the colour of air-dried 'fine earth' of each sample. The mean value of each plot was used for comparison by applying the Munsell notations.

3.7.5 Dry Matter and Loss-On-Ignition

On the fine earth, Dry Matter (DM) was determined on small (app. 6 gms) samples in porcelain crucibles dried overnight at 105°C. This sample was then brought to the muffle furnace maintained at 550°C and ignited for two hours to determine Loss-On-Ignition as percent (LOI%).

3.7.6 Mechanical Analysis

On fine earth, a modification of the plummet balance (Marshall, 1955) method was used in the mechanical analysis. The detailed procedure is described in Appendix III.

3.7.7 Clay Ratio

The results of particle distribution of sand, silt and clay, obtained by mechanical analysis, were used to calculate clay ratio; the ratio of sand plus silt to the clay, that is:

$$\text{Clay Ratio} = \frac{\text{sand + silt}}{\text{clay}}$$

3.7.8 Dispersion and Dispersion Ratio

Twenty-five grams of air-dried soil previously sieved to less than 2 mm particles was placed into a 1250 ml sedimentation cylinder and sufficient distilled water was added to make the volume up to 1250 ml. The cylinder was closed with a rubber stopper and shaken end over end 20 times. The suspension was allowed to settle as in mechanical analysis and 25 ml of the sample at a depth of 25 cm was pipetted and the dispersed silt and clay was determined by using a conical flask.

The Dispersion Ratio, the ratio of dispersed silt plus clay to the total silt plus clay (from mechanical analysis) was then calculated, that is -

$$\text{Dispersion Ratio } (\%) = \frac{\text{Dispersed Silt plus clay}}{\text{Total silt plus clay}} \times 100.$$

3.7.9 Aggregate Stability

To determine the aggregate stability of soil samples, a procedure was adopted from a method used to determine the effect of microbiological and organic matter treatments on the resistance of soil structure groups or clods to the action of raindrops (McCalla, 1944). A soil lump weighing 0.3 gms was placed on a 1 mm screen and hit by drops of distilled water 4.8 mm in diameter and falling 25 cm from a constant-head burette. A rate of one drop per 2.6 seconds was used; temperature of the distilled water was (21-25)^{o}C. The soil lump or aggregate was considered as destroyed when it was broken down and washed through the screen. The number of drops required to start breaking the lump and the total number of drops to destroy it were recorded. Five replicates were run on each soil sample and the mean value of the number of drops required was calculated on the basis of an 0.1 gm sample, that is the measured number of drops was divided by three (after McCalla, 1944).

3.7.10 Soil Reaction (pH)

On fine earth, soil/distilled water suspensions (1:2.5) were hand-stirred intermittently over four hours, and three pH readings taken, using a Radio-meter pH meter 22 equipped with glass-calomel electrodes. Mean pH was calculated to the nearest 0.1 unit.

3.7.11 Nitrogen and Phosphorus

Soil nitrogen and phosphorus levels were assessed with a Technicon Auto Analyser. Approximately 0.5 gm of an oven-dried (85^{0}C) sample was placed in a 150 ml conical flask and 6 ml of digestion mixture (1 gm of selenium powder and 200 gms of potassium sulphate in one litre of concentric sulphuric acid) added. The solutions were digested until clear, cooled and filtered into 100 ml volumetric flasks, and made up to the mark with distilled water. The solutions were then analysed on a Technicon Auto Analyser using alkaline phenate and sodium hypochlorite with a 625 millimicron colorimeter filter for nitrogen, ammonium molybdate and ascorbic acid with a 660 millimicron colorimeter filter for phosphorus.

3.7.12 Total Analysis for K, Na, Ca, Mg, Fe, Mn and Zn

Total analyses for K, Na, Ca, Mg, Fe, Mn and Zn were determined by flame photometry: The solutions were made as in the case of nitrogen and phosphorus except that 5 ml of digestion mixture (7:1 - 60% perchloric and concentrated sulphuric acid) were used with 15 ml of concentrated nitric acid for digestion. The solution obtained was then diluted with distilled water as follows:- Potassium - 1000 times; Sodium - 100 times; Calcium - 500 times; Magnesium - 500 times; Iron - 5000 times; Manganese - 100 times and Zinc - 100 times. Cations levels were then assessed separately by using a Varian Techtron AA5 model Atomic Absorption Spectrophotometer and were computed with the Tanton-Spain computer programme 'Peanut II'.

3.7.13 Soil Moisture Determination

Soil moisture was determined at $\frac{1}{3}$ BAR* (Field Capacity) and 15 BAR (Wilting Point) for each samples.

3.7.13.1 Soil Moisture at $\frac{1}{3}$ BAR

Soil moisture at $\frac{1}{3}$ BAR was determined by using a 1 BAR pressure plate extractor. Soil sample retaining rings were placed on the ceramic plate cell which accommodated 12 samples in the ring. Samples were levelled in the ring, covered with waxed paper and allowed to stand 16 hours with an excess of water on the plate. When the samples were saturated, excess water was removed from the ceramic plates with a pipette. The cells were mounted in the extractor and pressure in it built up to $\frac{1}{3}$ BAR using high-pressure nitrogen passed through a regulator. Moisture was allowed to flow from the outflow tubes for 48 hours. The samples were then weighed, dried overnight in an oven at 105^{o}C and reweighed. Moisture content at $\frac{1}{3}$ BAR was then determined as percent of dry-weight.

$$\text{Soil Moisture Content (\%)} = \frac{W_2 - W_3}{W_3 - W_1} \times 100$$

where W_1 = Wt. of moisture box

W_2 = Wt. of moisture box + wet soil

W_3 = Wt. of moisture box + oven dry soil.

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* The "BAR" is a standard unit for the expression of soil suction and is a unit of pressure equal to 10 dyne/cm. This is equivalent to 0.987 atmosphere or 14.5 PSI.

2.7.13.2 Soil Moisture at 15 BAR

Soil moisture at 15 BAR was determined by using a 100 BAR pressure membrane extractor. Controlled pressure was provided by a high pressure regulator connected directly to a tank of high-pressure nitrogen. The cellulose membrane was saturated by soaking it in distilled water for 24 hours and then placed on a screen drain plate. The samples, in thick plastic soil sample retaining rings, were placed on the cellulose membrane and saturated with distilled water. When saturated, the extractor was closed, 15 BAR (220 lbs/in^2) pressure applied and the samples allowed to drain for 48 hours. The samples were then weighed, dried overnight in an oven at 105°C and re-weighed. Moisture content at 15 BAR was then calculated as in 3.7.13.1.

3.7.14 Total Weight of Litter and Soil Organisms

The samples obtained as in 3.6.2 were transported to the laboratory, weighed and stored at 3°C.

Litter invertebrates were extracted by Mr H.M.G. Thomas, Forestry Department, A.N.U., by using modified Tullgren funnels. The litter was placed in sieves heated by overhead incandescent lighting which took the temperature in the sieves slowly up to 45°C over a period of 5 days. The invertebrates passed through the sieves with a lower chamber cooled by flowing water and fell into trays containing picric acid solution which killed and preserved them. The invertebrates were then filtered off and counted under a low power microscope. The extracted litter samples were then separated into their component parts, oven-dried at 85°C, and weighed.

3.8 ANALYSIS OF DATA

For analysis of data of each site, data from A and C were pooled together and data from 'B' plots were also pooled, after a preliminary test of all the parameters by using a 'BASTATS' computer programme for each plot. The final notation of groups for statistical analysis were thus as follows:-

GE1A + GE1C = GE1

GE2A + GE2C = GE2

GE1B + GE2B = GE3

GP1A + GP1C = GP4

GP2A + GP2C = GP5

GP1B + GP2B = GP6

SE1A + SE1C = SE1

SE1B = SE3

SP1A + SP1C = SP4

SP2A + SP2C = SP5

SP1B + SP2B = SP6

The basic statistics, mean, variance, standard deviation, coeff. of variance, G1, G2, K-S DMax, Standard error and 95% confidence limits for every soil parameter for each group were computed using a 'BASTATS' computer programme. Significant differences between each group were analysed by Student's 't' test.

CHAPTER 4

RESULTS

4.1 VEGETATIVE AND SOIL COVER

Natural eucalypt stands at the eucalypt plots on both shale and granite soils are of low quality and varied species composition but dominated mainly by red stringybark (*E. macrorhyncha*) and scribbly gum (*E. rossii*). Tree boles are of poor form and are unevenly-spaced, forming a stunted type of dry sclerophyll forest (Plates 4.1 and 4.2). The crowns are mostly free from each other because of uneven and sparse spacing of the trees (Plate 4.3). Much of the soil is well-covered with forest litter, and only a sparse covering of grasses and shrubs has developed.

The pine plots are in mature (40 yrs) *Pinus radiata* (Plates 4.5 and 4.6) forest. The pine crowns are also mostly free from each other (Plate 4.4) because of thinning carried out in 1969 and 1971. The cover of the forest-floor beneath the pines is continuous, firmly matted and appears more stable than underneath the eucalypts. Between trees and where the litter carpet is thinner natural regeneration is beginning to develop a definite stratum (Plate 4.5).

Where the pipeline passes through the pine plantation area, there is a well developed continuous ground cover of grasses and clovers (Plate 4.7 and 4.8), the result of fertiliser and seeding programmes carried out after the pipeline was constructed. On the other hand, in the eucalypt area only a sparse ground cover has developed after

PLATE 4.1 Stunted Sclerophyll Forest at Plot SE 1A

PLATE 4.2 Stunted Sclerophyll Forest at Plot GE 2A

Note – The amount of leaf litter compared with SE 1A above.
Divisions on the stake are 5 cm.

PLATE 4.3 Eucalypt Crown Cover at Plot GE 1A

PLATE 4.4 Pine Crown Cover at Plot GP 1A

PLATE 4.5 Mature *Pinus radiata* at Plot GP 1A

PLATE 4.6 Mature *Pinus radiata* at Plot GP 2A

PLATE 4.7 Well Developed Ground Cover at Plot GP 1B

PLATE 4.8 Well Developed Ground Cover at Plot GP 2B

the fertilizer and seeding treatments, especially on SE1B (Plate 4.9). There are no bare areas along the revegetated bench of the pipeline (Plates 4.11 and 4.12), except where crossed by roads. There are very few native species established on the pipeline bench in the plantation, except at its junction with the eucalypt forest where there is a variable cover of native pioneer species (Plate 4.10).

Table 4.1 shows the canopy and ground cover density for each plot.

In the study area, the average canopy cover on soils of granite origin is 70% under eucalypts, 55% under pine and 5% on the gravity main; on soils of shale origin the canopy cover density is 55% under eucalypts, 48% under pine and 7% on the gravity main. The average ground vegetative cover on soils of granite origin is 92% under eucalypts, 95% under pine and 80% on the gravity main revegetated area. On soils of shale origin it is 61% under eucalypt, 81% under pine and 66% on the gravity main revegetation. Generally the most significant ground vegetative cover is grass and clover on the gravity main and leaf cover under eucalypt and pine on soils of both types of origin, except at plots GP2B, SP1B and SP2B where pine needles from nearby pine trees are the dominant vegetative cover.

By intercepting the rainfall, a vegetative cover protects the soil surface from structural deterioration by the direct impact of rainfall drops, and higher infiltration capacities result in soils developed under the protection produced by native and pine forests.

Thus in the presence of adequate cover both the detaching and transporting power of rainfall is minimised. The importance of

PLATE 4.9 Discontinuous Ground Cover at Plot SE 1B

PLOT 4.10 Native Pioneer Species Along the Gravity Main Pipeline

PLATE 4.11 Pipeline Bench Revegetation During Winter at Site SP 1B

PLATE 4.12 The Same Site During Summer

TABLE 4.1 Cover Density. Point Height Intercepts

No.	Plots	Cover Density - Percentage (%)									Remarks
		Canopy	GROUND								
			Vegetation					Soil Mantle			
			Leaf	Bark	Branch	Grass & Clover	Total	Bare Rock	Bare Soil	Total	
1	GE 1A	65	56	3	10	3	72	19	9	28	
2	GE 1B	5	–	–	–	82	82	–	18	18	
3	GE 1C	85	67	5	11	15	98	2	–	2	
4	GE 2A	77	72	6	18	1	97	3	–	3	
5	GE 2B	4	3	–	–	62	65	–	35	35	
6	GE 2C	55	29	10	3	58	100	–	–	–	
7	GP 1A	50	64	–	8	18	90	2	8	10	
8	GP 1B	4	10	–	11	71	92	–	8	8	
9	GP 1C	81	37	1	13	40	91	7	2	91	Thick undergrowth, pine seedlings
10	GP 2A	40	71	–	7	22	100	–	–	–	
11	GP 2B	7	64	–	3	14	81	–	19	19	Leaf needles from nearby pine trees
12	GP 2C	51	43	–	3	54	100	–	–	–	
13	SE 1A	49	38	7	13	–	58	15	27	42	
14	SE 1B	11	2	–	3	19	24	–	76	76	Shrub canopy
15	SE 1C	58	36	6	20	2	64	11	25	36	
16	SP 1A	40	47	–	18	4	69	22	9	31	
17	SP 1B	3	47	–	1	31	79	–	21	21	Leaf needles from nearby pine trees
18	SP 1C	72	62	–	5	13	80	8	12	20	
19	SP 2A	43	45	2	25	8	80	8	12	20	
20	SP 2B	–	42	–	3	27	72	–	28	28	Leaf needles from nearby pine trees
21.	SP 2C	36	64	–	15	16	95	–	5	5	

cover has been confirmed by many workers (Meeuwig, McClurkin, Molchanov, Leyton, Tadmor and Shanan - op.cit. in 2.6.1). According to Smith and Wischmeier (op. cit. p. 10) "The greatest deterrent to soil erosion is cover". Packer (op. cit. p. 38) prescribed ground cover density of at least 70% to maintain soil stability.

In the study area the average cover density on soils of granite origin is well over 70% (Eucalypt 92%, Pine 95%, Gravity Main 80%), and on soils of shale origin is over 70% under pine (81%) and close to 70% under eucalypt (61%) and on the gravity main revegetation (66%). It can be expected therefore that both granite and shale soils under eucalypt and pine and the gravity main revegetation maintain their soil stability.

In terms of percentage vegetative ground cover (Table 4.1) the pine forest is the best in all cases, i.e., on both granite and shale soils. On granite soils the ranking on the basis of the average percentage of vegetation ground cover derived from Table 4.1 is pine, eucalypt, gravity main and on shale soils pine-gravity-eucalypt.

In comparing soil origin, granite soil produced a greater vegetative ground cover than soil of shale origin and the granite soils are likely to receive the greater protection from soil erosion by vegetative ground cover.

4.2 FOREST LITTER AND SOIL ORGANISMS

Forest litter accumulation is well developed under eucalypt and pine forests within the study area, while the green vegetative cover on pipeline revegetated plots is similarly well developed for protection from raindrop impact (Plate 4.13). A summary of the mean values of oven dry weight of litter components for all sites is shown in Table 4.2.

TABLE 4.2 Mean Values of Litter for All Sites

Sites/ /Litter	Oven Dry Wt. of Litter Kg/m²				
	Leaf Litter	Bark Litter	Humus	Total	
				Mean	Standard Error
GE1	0.35	0.66	1.05	2.06	0.34
GE2	0.28	0.80	0.79	1.87	0.18
GP4	0.13	0.88	1.23	2.24	0.50
GP5	0.15	0.15	0.64	0.94	0.15
SE1	0.25	0.66	0.84	1.76	0.30
SP4	0.16	0.47	0.92	1.55	0.37
SP5	0.11	0.73	0.77	1.61	0.45

Mean value of 8 samples per site

A summary of reported values for the accumulation of litter under different forest types is shown in Table 4.3.

a - Under Eucalypt Forest SE 1C

b - Under Pine Plantation SP 2C

c - Green Vegetation on Gravity Main Pipeline GP 1B

PLATE 4.13 Well Developed Forest Litter Accumulation

TABLE 4.3 Accumulation of Litter Under Different Forest Types

Vegetation & Species	Site	Oven Dry Wt. of Forest Litter Kg/m^2	Reference
Pine Plantations			
Pinus radiata (18 yr)	Kowen	1.52	Hamilton, 1964
" (19 yr)	"	1.47	"
" (28 yr)	Pierces Ck.	1.69	"
" (29 yr)	"	2.29	"
" (23 yr)	Brindabella	2.45	"
" (30 yr)	"	2.02	"
" (39 yr)	Kowen	3.50	Bridges, 1968
" (12 yr)	Tumut	1.70	Ovington, 1970
" (14 yr)	Uriarra	0.98	Thistlethwaite, 1970
" (18 yr)	"	2.18	"
" (28 yr)	"	0.63	"
" (34 yr)	"	0.95	"
" (30 yr)	Sand-dune SA, SQ II	2.26	Lamb, 1972
" (30 yr)	" SQ V	1.62	"
" (40 yr)	" SQ II	2.44	"
" (40 yr)	" SQ V	2.25	"
Pinus taeda (32 yr)	Madison County, Tennessee	3.18	McClurkin, 1967
Pinus echinata (32 yr)	"	2.57	"
Pinus palustris (32yr)	"	2.31	"
Pinus elliottii (32 yr)	"	2.14	"
Indigenous			
Dry sclerophyll	Kowen	2.44	Hamilton, 1964
"	"	2.74	"
"	Pierces Ck.	2.12	"
"	"	2.75	"
"	Brindabella	2.23	"
Wet sclerophyll	"	2.46	"
Dry sclerophyll	Kowen	1.30	Bridges, 1968
Hardwood spp.	Madison County, Tennessee	1.14	McClurkin, 1967

Within the study area, the total oven dry weight of forest litter accumulated is not significantly different (Table 4.4) between sites except for GP5 where litter accumulation is less (Table 4.2) compared to the other sites.

TABLE 4.4 Summary of Significant Differences Between Total Weight of Forest Litter. (Student's "t" test)

Site	SP 5	SP 4	SE 1	GP 5	GP 4	GE 2	GE 1
GE 1	NS	NS	NS	**	NS	NS	-
GE 2	NS	NS	NS	**	NS	-	
GP 4	NS	NS	NS	*	-		
GP 5	NS	NS	*	-			
SE 1	NS	NS	-				
SP 4	NS	-					
SP 5	-						

NS - Not significant at $p = 0.05$
* - Significant at $p = 0.05$
** - " at $p = 0.01$
df - degree of freedom in all cases is 14.

Total oven dry weight of litter under eucalypt ranged from 1.75 to 2.06 kg/m^2, and from 0.94 to 2.24 kg/m^2 (Table 4.2) under pine plantations within the study area.

The litter and humus layers of forests provide extra protection from the direct impact of raindrops, apart from improving the soil infiltration capacity. Lowdermilk (op. cit. p. 33) concluded from a study of the influence of litter on runoff, percolation and erosion that the ability of litter to store water was not as hydrologically important as its dual role in maintaining a permeable soil structure and in acting as a filter for turbid runoff. Other beneficial effects of litter are - reduction of evaporation from the soil surface, reduction of runoff velocity and reduction of erosive capacity of surface runoff (Kittredge, 1948; Molchanov, op. cit. p. 39). Gilmour (op. cit. p. 15) stated that the amount of ground cover was more important than the type of cover in controlling surface runoff on similar soils to this study. Soil loss was negligible from plots with more than 0.72 Kg/m^2 of ground cover, but a marked increase in soil loss resulted from cover reduction below this value. Thus according to Gilmour's observation, the sites under eucalypt and pine on soils of shale & granite origin accumulated more than enough biomass of forest litter to control surface runoff and soil loss.

A summary of the mean values of total soil invertebrates for all sites is shown in Table 4.5.

TABLE 4.5 Mean Values of Soil Invertebrates for All Sites

Site	Soil Invertebrates in Litter Nos/1/16m^2											
											Total	
	Acarina	Collembola	Coleoptera	Diptera	Aranae	Hyteroptera & Homoptera	Hymenoptera	Thysanoptera	Myriapoda	Other	Mean	S.E.
GE 1	90	3	4	5	4	2	10	8	1	3	129.75	37.25
GE 2	57	2	2	1	1	0	4	5	0	1	73.13	18.39
GP 4	261	277	4	2	1	7	3	5	4	5	569.25	224.13
GP 5	50	82	1	2	0	3	2	2	1	0	143.50	63.76
SE 1	27	2	3	1	0	1	2	1	1	1	39.38	9.54
SP 4	49	10	1	1	2	10	1	3	1	1	78.75	28.62
SP 5	17	4	1	1	0	4	0	3	1	1	31.25	10.17

The total number of invertebrates found in forest litter is significantly correlated ($p = 0.05$) to the oven dry weight of the litter (Table 4.6) in all cases. It is also significantly correlated to the oven dry weight of humus, except under eucalypt forest on granite soil.

TABLE 4.6 Summary of the Coefficient Correlation Between Total Population of Invertebrates and Litter Components

Geology & Vegetation	df	Coefficient Correlation "r" Between Total Population Numbers of Invertebrates and Oven Dry Weight of Litter Components			
		Leaf	Bark	Humus	Total
Granite - Eucalypt	14	0.4820 NS	0.2965 NS	0.0727 NS	0.5308*
" - Pine	14	0.3039 NS	0.4795 NS	0.5371 *	0.5230*
Shale - Eucalypt	6	0.0198 NS	0.5184 NS	0.8584 *	0.7870*
" - Pine	14	0.3451 NS	0.2183 NS	0.7747***	0.5477*

NS - Not significant in correlation at 0.05 level
* - Significantly correlated at 0.05 level
*** - Significantly correlated at 0.001 level
df - degree of freedom

Bennett (op. cit. p. 18) stated that the activities of soil micro-organisms upon organic matter tend to develop a desirable crumb or granular structure that offers marked resistance to erosion and favours easy penetration by plant roots and rain water. Millar _et_. _al_., (1965) also stated that other groups of animals inhabiting the soil such as rodents, ants, snails, spiders, mites, millipedes, centipedes and various other worms and insects, have direct effects on the soil by their activities, which improve soil aeration and drainage.

The study indicated that there were significant populations of soil invertebrates at each site and while there may be other biological implications they would contribute to the development of a soil structure that reduces the risk of erosion.

4.3 SOIL PROPERTIES

4.3.1 Colour

The surface soil colours were similar under pine and eucalypt for soils of both shale and granite origin. They were found to fall within the range of colour chips on the Munsell soil colour chart "HUE 10 YR" for all plots except SE1A, which is "HUE 7.5 YR". Within each plot 5 composite samples (air dry) were taken: The calculated average "VALUE" and "CHROMA" values are shown in Table 4.7.

The "VALUE" under pine ranged from 4 to 6 on granite and was 6 on shale soil; under eucalypt it ranged between 5 and 6 on granite and 4 to 6 on soil of shale origin, whereas on the pipeline revegetation, the "VALUE" equalled 7 except SE1B which was 6. The "CHROMA" ranged between 2 & 3 under pine, 2 & 4 under eucalypts and 3-4 on pipeline revegetation, on soils of both granite and shale origin.

TABLE 4.7 Summary of Surface Soil Colour

No.	Plots	Colour Name	Munsell Notation
1	GE 1A	Light brownish gray	10 YR 6/2
2	GE 1B	Very pale brown	10 YR 7/3
3	GE 1C	Light yellowish brown	10 YR 6/4
4	GE 2A	Pale brown	10 YR 6/3
5	GE 2B	Very pale brown	10 YR 7/3
6	GE 2C	Grayish brown	10 YR 5/2
7	GP 1A	Dark grayish brown	10 YR 4/2
8	GP 1B	Very pale brown	10 YR 7/4
9	GP 1C	Grayish brown	10 YR 5/2
10	GP 2A	Light brownish gray	10 YR 6/2
11	GP 2B	Very pale brown	10 YR 7/4
12	GP 2C	Light brownish gray	10 YR 6/2
13	SE 1A	Dark brown	7.5 YR 4/3
14	SE 1B	Pale brown	10 YR 6/3
15	SE 1C	Light yellowish brown	10 YR 6/4
16	SP 1A	Pale brown	10 YR 6/3
17	SP 1B	Very pale brown	10 YR 7/3
18	SP 1C	Light brownish gray	10 YR 6/2
19	SP 2A	Pale brown	10 YR 6/3
20	SP 2B	Very pale brown	10 YR 7/4
21	SP 2C	Light brownish gray	10 YR 6/2

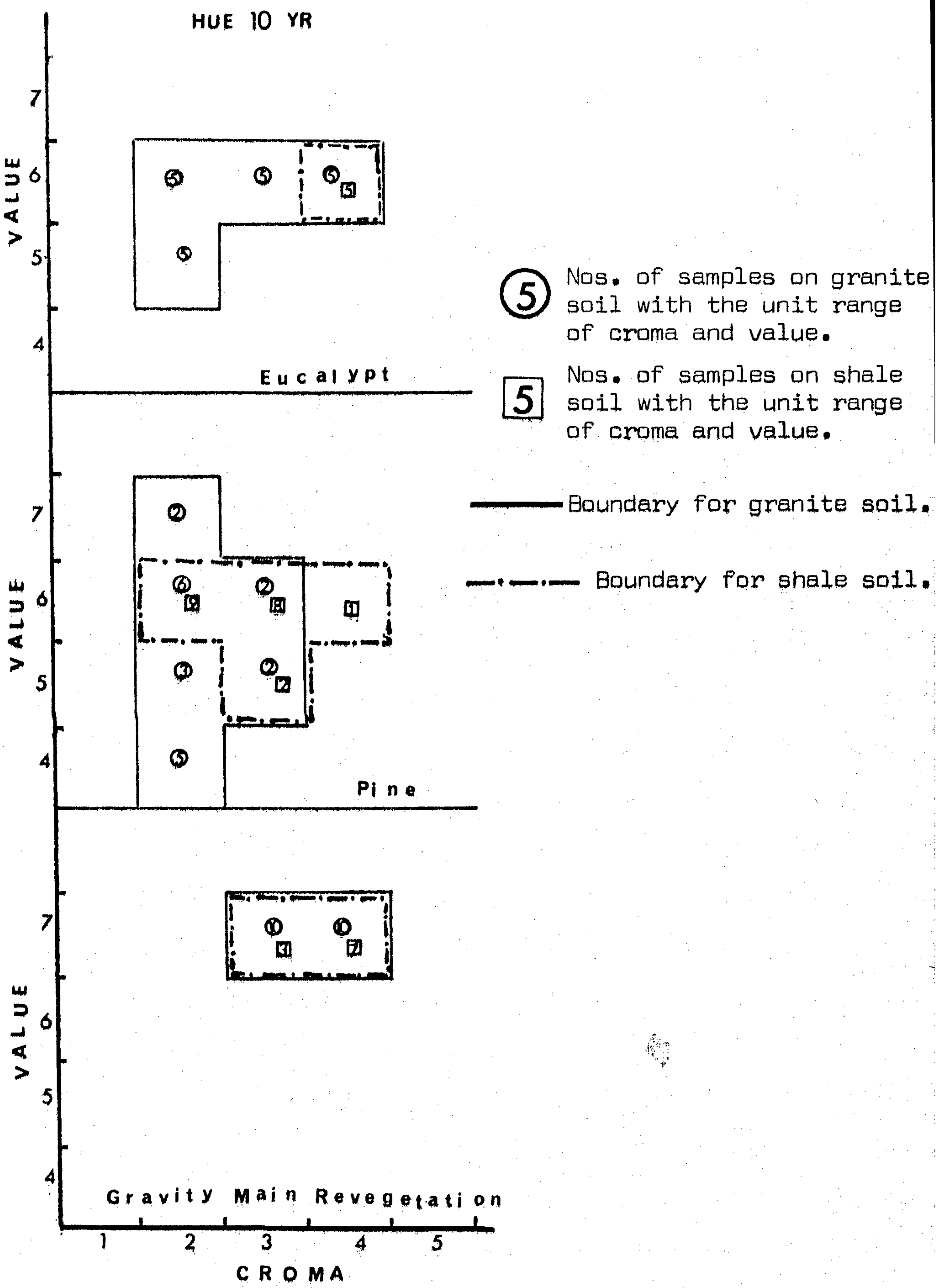

FIGURE 4.1 Diagrammatic Representation of Surface Soil Colour

The resulting 100 colour values (i.e. 5 in each of 20 plots), are plotted in Figure 4.1 to show the marked separation of eucalypt, pine and gravity main revegetation. The black and brown colour of the soil is mainly due to the presence of organic matter which in turn favours soil structure. In this study, the soils under pine and eucalypt were within the same range but both showed marked differences from the colour of the soil on gravity main revegetation which indicated a lower content of organic matter which would in turn affect the structural stability of the soil.

4.3.2 Penetration

The penetration values at the different sites are given in Table 4.8. Each value is the mean of 40 observations/site except for SE3 where only 20 observations were made.

TABLE 4.8 Mean Value of Penetration

Site	Penetration Kg/cm^2	
	Mean	S.E.
GE 1	0.47	0.12
GE 2	0.29	0.03
GE 3	2.73	0.31
GP 4	0.60	0.11
GP 5	0.46	0.10
GP 6	3.20	0.18
SE 1	1.08	0.12
SE 3	4.20	0.25
SP 4	1.14	0.18
SP 5	1.09	0.17
SP 6	4.78	0.10

A summary of significant differences in penetration between sites is shown in Table 4.9.

TABLE 4.9 Summary of Significant Difference in Penetration Between Sites (Student's "t" test)

Site	SP 6	SP 5	SP 4	SE 3	SE 1	GP 6	GP 5	GP 4	GE 3	GE 2	GE 1
GE 1	***	**	**	***	**	***	NS	NS	***	NS	-
GE 2	***	***	***	**	***	***	NS	*	***	-	
GE 3	***	***	***	**	***	NS	***	***	-		
GP 4	***	*	*	***	**	***	NS	-			
GP 5	***	**	**	***	***	***	-				
GP 6	***	***	***	**	***	-					
SE 1	***	NS	NS	***	-						
SE 3	*	***	***	-							
SP 4	***	NS	-								
SP 5	***	-									
SP 6	-										

NS - Not significant at $p = 0.05$
* - Significant at $p = 0.05$
** - Significant at $p = 0.01$
*** - Significant at $p = 0.001$
df = 18, except with SE3, where it is 13.

On both granite and shale derived soils, penetration varies little between soils under pine and under eucalypts, but on the gravity main revegetation area the penetration value is significantly higher than the values under both eucalypt and pine. Under similar types of vegetation, penetration values on shale soils are higher than the values on granite soils. Within the same type of soil and the same vegetation, the value of penetration on steep slopes is higher than the value on shallow slopes.

The above results from penetration tests indicate that compaction of granite soil is lower than for shale soil, and given the same type of soil and vegetation, compaction is lower on a shallow slope than on a steep slope. Since compaction is higher on the gravity main revegetated area than on both the pine and eucalypt forest, porosity will be the lowest on the gravity main revegetation in all cases, regardless of slope or soil origin.

4.3.3 Particle Size Distribution

Mechanical analysis was done on fine earths, that is, smaller than 2 mm in diameter. The results for each plot are given in Appendix IV A. Particle size distribution for individual classes, and cumulative percentage of particle sizes were calculated and are shown in Appendices IV B and IV C. Mean values of mechanical analysis, particle size distribution, and cumulative percentage of particle sizes, for each site are given in Table 4.10. The particle size grading curves for all sites are presented in Fig. 4.2.

Ellison (op. cit. p. 29) suggested that determination of particle and aggregate sizes carried by rain drop splash and surface flow under field conditions may make it possible to identify erosional deposits caused by splash and surface flow. He found that some of the larger soil aggregates were broken down by the rainfall

TABLE 4.10 Summary of Particle Sizes Distribution of Surface Soils

No.	Site	Mechanical Analysis of Fine Particles < 2 mm (%)					Particle-size Distribution Calculated (% Wt.)						Particle Size: Cumulative Percentage				
		Coarse Sand 2.0 – 0.2	Fine Sand 0.2 – 0.02	Silt 0.02–0.002	Clay <0.002	Org. Matter	Coarse Part. >2 mm	CS 2.0 – 0.2	FS 0.2 – 0.02	Si 0.02–0.002	Cl <0.002	Org. Matter	+2.0	+0.2	+0.02	+0.002	+0.0
1	GE 1	51.71 (1.76)	18.03 (1.02)	14.35 (0.62)	8.10 (0.44)	7.81	37.43 (3.98)	32.35	11.28	8.98	5.07	4.89	37.43	69.78	81.06	90.04	95.11
2	GE 2	32.48 (2.02)	20.11 (0.92)	20.80 (0.87)	13.10 (0.59)	13.58	25.70 (2.99)	24.13	14.94	15.45	9.73	10.09	25.70	49.83	64.77	80.22	89.95
3	GE 3	44.46 (2.78)	21.59 (0.74)	12.60 (0.67)	16.45 (1.69)	4.90	36.05 (2.39)	28.43	13.81	8.06	10.52	3.13	36.05	64.48	78.29	86.35	96.87
4	GP 4	43.88 (1.08)	20.31 (1.38)	18.95 (1.57)	10.25 (0.59)	6.61	26.56 (4.88)	32.23	14.92	13.92	7.53	4.85	26.56	58.79	73.71	87.63	95.16
5	GP 5	36.11 (4.50)	24.20 (0.79)	20.70 (3.09)	12.15 (1.80)	6.84	12.68 (1.50)	31.53	21.13	18.08	10.61	5.97	12.68	44.21	65.34	83.42	94.03
6	GP 6	49.62 (1.04)	23.23 (0.46)	12.10 (0.39)	11.25 (0.40)	3.80	25.51 (2.90)	36.96	17.30	9.01	8.38	2.83	25.51	62.47	79.77	88.78	97.16
7	SE 1	38.40 (1.77)	14.83 (0.57)	18.85 (1.09)	20.55 (0.86)	7.37	48.57 (2.88)	19.75	7.63	9.69	10.57	3.79	48.57	68.32	75.95	85.64	96.21
8	SE 3	34.70 (1.06)	22.10 (1.82)	22.70 (0.85)	17.40 (0.29)	3.10	45.70 (2.45)	18.84	12.00	12.33	9.45	1.68	45.70	64.54	76.54	88.87	98.32
9	SP 4	34.53 (0.74)	16.27 (0.81)	24.40 (0.34)	15.40 (0.48)	9.40	47.33 (2.98)	18.19	8.57	12.85	8.11	4.95	47.33	65.52	74.09	86.94	95.05
10	SP 5	46.31 (3.08)	18.93 (1.04)	16.50 (0.87)	11.50 (1.80)	6.76	39.02 (2.42)	28.24	11.54	10.06	7.01	4.12	39.02	67.26	78.80	88.86	95.87
11	SP 6	41.64 (1.98)	18.75 (0.62)	17.10 (0.97)	18.00 (0.67)	4.51	37.41 (3.11)	26.06	11.74	10.70	11.22	2.82	37.41	63.47	75.21	85.91	97.18

Note: Figures in brackets are the Standard Error of the Mean

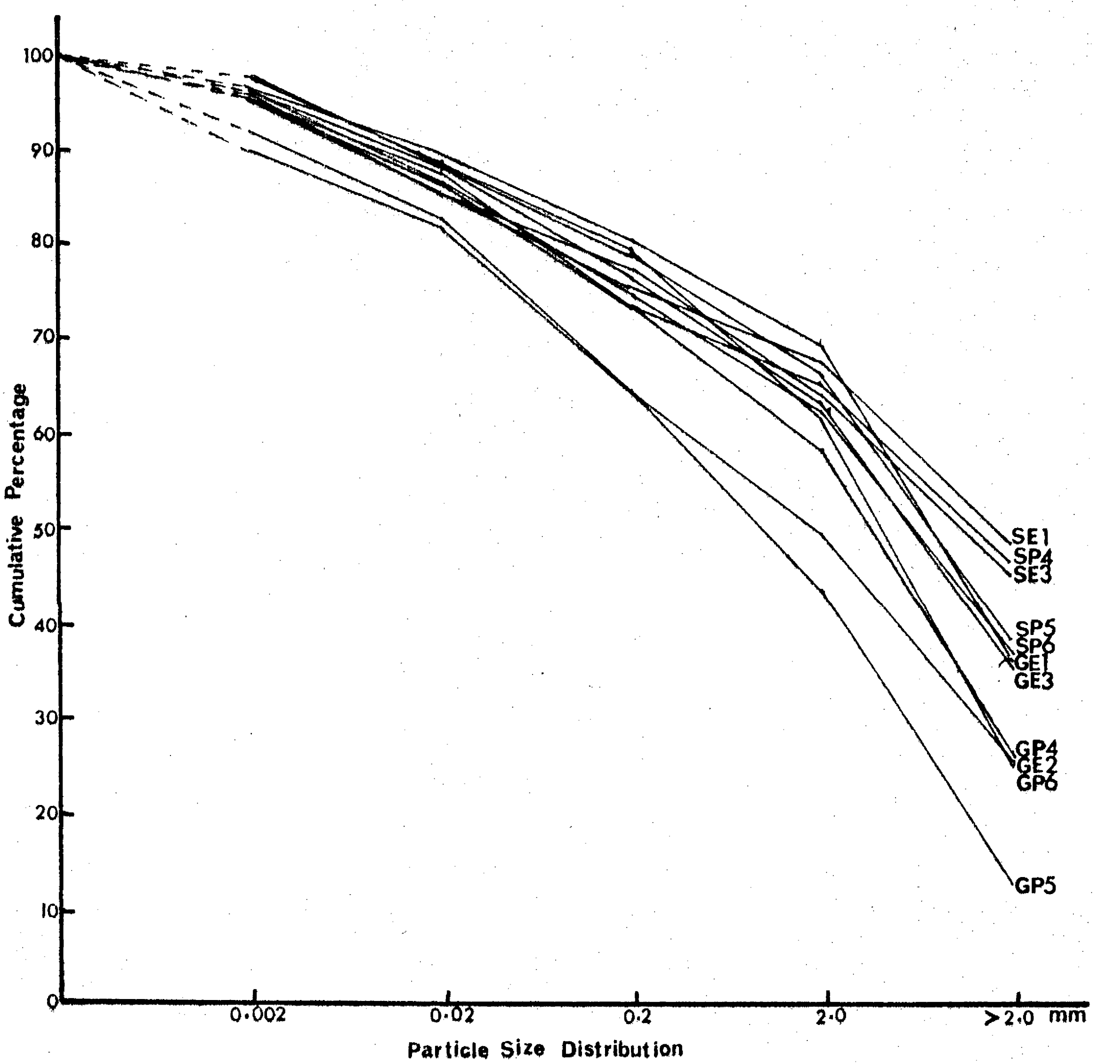

FIGURE 4.2 Particle-size Grading Curves for Surface Soils

so that soil materials on the surface flow were composed of about 95 percent silt plus clay and 5 percent sand plus gravel. Balci (op. cit. p.33) used rainfall simulation to investigate properties of eastern and western Washington forest soils to determine correlations between soil erodibility and measurable differences in soil properties. He found that erodibility had significant inverse associations with percent silt. Bryan (op. cit. p. 19) explained that aggregate size distribution is important in erosion processes because aggregates below a certain size may be removed by erosion without previous dispersion. He also observed that there was high negative correlation between clay and total soil loss and significantly high correlation between sand content and soil loss, except for soils with a sand content above 85%, which showed relatively low erodibility. Farmer (op. cit. p. 29) determined the relative detachability of 11 soil-size fractions of disturbed surface soil mass of two coarse-grained granite soils and a fine-textured clay soil under simulated rainfall. By comparing the proportion of a given size fraction in the pre-treatment soil mass with the proportion of that size fraction in the splashed soil, he found that without overland flow, soil particle sizes in the range of 110–1,450 µm were most susceptible to detachment by raindrop impact. With overland flow, the susceptible size range was 219–2,034 µm. He concluded that particle detachability appears to be strongly influenced by three factors:-

(i) particle size;

(ii) type of particle, aggregate or grain; and

(iii) the presence or absence of a thin sheet of surface detension water.

TABLE 4.11 Summary of Significant Differences of Particle Sizes Between Sites (Student's 't' test)

a - Coarse Sand %

Granite

	6	5	4	3	2	1	
1	NS	**	**	*	***		1
2	***	NS	***	**			2
3	NS	NS	NS			NS	3
4	**	NS		NS		NS	4
5	**		**	*		*	5
5		NS	**	*		NS	6
	6	5	4	3	2	1	

Shale

b - Fine Sand %

Granite

	6	5	4	3	2	1	
1	***	***	NS	*	NS		1
2	**	**	NS	NS			2
3	NS	*	NS			***	3
4	NS	*		***		NS	4
5	NS		NS	NS		**	5
6		NS	*	*		***	6
	6	5	4	3	2	1	

Shale

1 = Eucalypt - steep slope
2 = Eucalypt - shallow slope
3 = Eucalypt - gravity main

4 = Pine - steep slope
5 = Pine - shallow slope
6 = Pine - gravity main

c - Silt %

Granite

	6	5	4	3	2	1	
1	**	NS	*	NS	***		1
2	***	NS	NS	***			2
3	NS	*	**			*	3
4	***	NS		*		***	4
5	*		***	***		NS	5
6		NS	***	**		NS	6
	6	5	4	3	2	1	

Shale

d - Clay %

Granite

	6	5	4	3	2	1	
1	***	*	**	***	***		1
2	*	NS	**	NS			2
3	**	NS	**			*	3
4	NS	NS		*		***	4
5	NS		NS	*		***	5
6		**	**	NS		*	6
	6	5	4	3	2	1	

Shale

NS - Not significant at $p = 0.05$
* - Significant at $p = 0.05$
** - Significant at $p = 0.01$
*** - Significant at $p = 0.001$

In this study, the analysis of particle size distribution indicated significant differences within the sites (Table 4.11), but there does not seem to be a marked difference in particle size distribution because of management practices. Significant decreases in clay particle content occurred when eucalypt was converted to pine, and revegetated grass showed a higher erodibility status, thus supporting the work of Balci, Bryan and Farmer.

4.3.4 Dispersion

Mean values of total silt plus clay (from mechanical analysis), dispersed silt plus clay and the coefficient correlation between total (silt + clay) and dispersed (silt + clay) are shown in Table 4.12.

TABLE 4.12 Total Silt Plus Clay, Dispersed Silt Plus Clay, and Coefficient Correlation Between Total (Silt + Clay) and Dispersed (Silt + Clay) for the Site

Parameter / Site	Total Silt + Clay %		Dispersed Silt + Clay %		Coefficient Correlation		
	Mean	95% Conf. Limits	Mean	95% Conf. Limits	df	"r"	
GE 1	22.45 ±	1.91	8.29 ±	1.84	8	0.5947	NS
GE 2	33.90 ±	3.09	12.11 ±	1.88	8	0.5877	NS
GE 3	29.05 ±	5.06	9.16 ±	1.78	8	0.8433	**
GP 4	29.20 ±	4.39	9.92 ±	1.74	8	0.7513	*
GP 5	32.85 ±	11.01	10.10 ±	1.18	8	0.2923	NS
GP 6	23.35 ±	1.43	8.92 ±	0.77	8	0.7619	*
SE 1	39.40 ±	5.20	6.68 ±	0.71	8	0.2478	NS
SE 3	40.10 ±	3.15	13.56 ±	1.94	3	0.1743	NS
SP 4	39.80 ±	1.30	11.98 ±	2.99	8	0.0652	NS
SP 5	28.00 ±	5.42	12.68 ±	1.47	8	0.2867	NS
SP 6	35.10 ±	3.17	10.63 ±	1.60	8	0.3822	NS

NS - Not significantly correlated at 0.05 level
* - Significantly correlated at 0.05 level
** - Significantly correlated at 0.01 level
df - degree of freedom

Within the study area, total (silt + clay) and dispersed (silt + clay) are not correlated with each other at each site (Table 4.12), that is, the dispersion of a given soil does not depend upon the total (silt + clay) composition in the soil. Soil of the same origin under the same type of vegetation is dispersed more on a shallow slope than on a steep slope. On soils of granite origin, dispersion under pine and eucalypt, pine and gravity main revegetation, and eucalypt and gravity main revegetation are not significantly different, (Table 4.13). However on soils of shale origin, the soil under eucalypt appears to be the least dispersed compared to the soils under pine and gravity main revegetation.

TABLE 4.13 Summary of Significant Differences Between Dispersed Silt Plus Clay (Student's 't' test)

	Granite						
	6	5	4	3	2	1	
1	NS	NS	NS	NS	**		1
2	**	NS	NS	*			2
3	NS	NS	NS			***	3
4	NS	NS		NS		**	4
5	NS		NS	NS		***	5
6		*	NS	*		***	6
	6	5	4	3	2	1	
	Shale						

NS - Not significant at p = 0.05
* - Significant at p = 0.05
** - Significant at p = 0.01
*** - Significant at p = 0.001

1 - Eucalypt - Steep slope
2 - Eucalypt - Shallow slope
3 - Eucalypt - Gravity main
4 - Pine - Steep slope
5 - Pine - Shallow slope
6 - Pine - Gravity main

4.3.5 Soil Moisture Content

Mean values of surface soil moisture content at $\frac{1}{3}$ BAR (Field Capacity) and 15 BAR (Wilting Point) are given in Table 4.14 and are plotted in Fig. 4.3 for each site.

TABLE 4.14 Mean Values: Surface Soil Moisture Content

Parameter / Site	Soil Moisture Content (%)					
	Field Capacity		Wilting Point		Available Moisture	
	Mean	95% Conf. Limits	Mean	95% Conf. Limits	Mean	95% Conf. Limits
GE 1	16.46 ±	1.94	8.24 ±	1.05	8.22 ±	1.67
GE 2	21.68 ±	2.21	8.40 ±	1.71	13.28 ±	1.07
GE 3	15.20 ±	1.95	6.39 ±	1.33	8.81 ±	0.90
GP 4	19.75 ±	2.25	9.90 ±	1.83	9.85 ±	1.33
GP 5	18.45 ±	5.44	8.00 ±	1.84	10.45 ±	4.24
GP 6	15.43 ±	0.82	5.62 ±	0.41	9.81 ±	0.48
SE 1	23.86 ±	1.57	9.76 ±	1.42	14.10 ±	1.38
SE 3	20.32 ±	1.24	6.37 ±	0.67	13.95 ±	0.96
SP 4	22.19 ±	1.97	7.47 ±	1.57	14.72 ±	1.57
SP 5	15.93 ±	3.67	5.89 ±	1.78	10.04 ±	2.02
SP 6	16.48 ±	2.39	7.65 ±	0.69	8.83 ±	1.76

Barnett and Rogers (1966) identified soil parameters for predicting soil erodibility and runoff potential of cultivated fallow soil through regression analyses of the soil and site physical properties with known values of rainfall, effective intensity, runoff, and soil loss from tests with a rainfall simulator. They stated that an erosion prediction equation may permit the determination of soil-site erosion and runoff potential through simple field and laboratory determinations of soil-site physical properties alone. They included soil moisture content at $\frac{1}{3}$ and 15

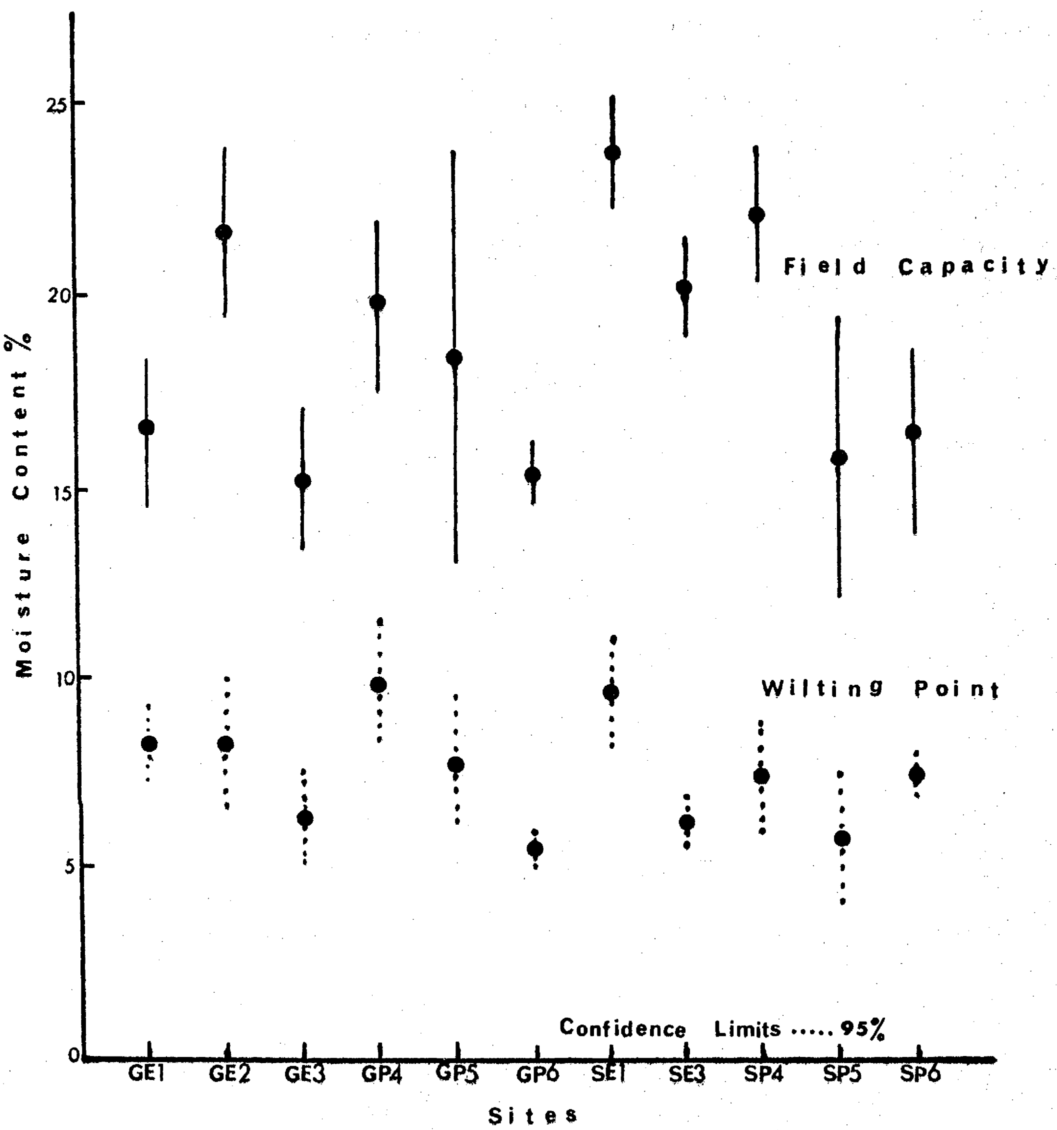

FIGURE 4.3 Moisture Contents Showing Field Capacity and Wilting Point.

atmospheres tension as field parameters necessary to be measured. Balci (op.cit. p. 33) also reported that soil erodibility had significant increased associations with the permanent wilting point, i.e., the soil moisture at 15 atmospheres tension.

Soil moisture content at $\frac{1}{3}$ BAR and 15 BAR are significantly different between some sites (Fig. 4.3) but there are no clear differences in soil moisture content which can be attributed to either forest management or engineering practices.

4.3.6 Soil Reaction (pH)

The mean pH values at different sites are given in Table 4.15.

TABLE 4.15 The Mean pH Values at Different Sites

Site	pH	
	Mean	S.E.
GE 1	5.6	0.17
GE 2	5.2	0.15
GE 3	5.6	0.11
GP 4	5.7	0.05
GP 5	5.7	0.10
GP 6	5.8	0.05
SE 1	4.5	0.07
SE 3	5.3	0.12
SP 4	5.1	0.10
SP 5	5.3	0.08
SP 6	5.4	0.06

Under the same type of vegetation and slope, the pH values on shale soil were lower than the values on granite soil.

Within soils of the same origin (both granite and shale), a change of forest cover from eucalypt to pine resulted in an increase in pH values of 0.1 to 0.6 units. Engineering practices and revegetation also caused a slight increase in pH (0.1 - 0.3 units), except on SE 3 (pH = 5.3) where the pH was 0.8 units higher than on the adjacent eucalypt site SE 1 (pH = 4.5) which was the most acidic site within the study area.

In analysing the data for change in pH as a result of forestry and engineering practices, comparisons must be made with soils of the same origin rather than between soils although there are in some sites significant differences in pH between soil types. The data within the study area showed that:-

(1) For sites GE 1, GE 2, GE 3 (Table 4.15 and 4.16) there is no significant difference in pH values and on this basis it appears that the engineering works on the granite soils have not changed the soil acidity.

TABLE 4.16 Summary of Significant Differences Between pH Values (Student's 't' test)

	Granite						
	6	5	4	3	2	1	
1	NS	NS	NS	NS	NS		1
2	**	**	**	NS			2
3	*	NS	NS			***	3
4	NS	NS		NS		***	4
5	NS		NS	NS		***	5
6		NS	*	NS		***	6
	6	5	4	3	2	1	
	Shale						

NS - Not significant at p = 0.05
* - Significant at p = 0.05
** - Significant at p = 0.01
*** - Significant at p = 0.001

1 = Eucalypt - Steep Slope
2 = Eucalypt - Shallow Slope
3 = Eucalypt - Gravity Main
4 = Pine - Steep Slope
5 = Pine - Shallow Slope
6 = Pine - Gravity Main

(2) There is a highly significant difference between sites SE 1 and SE 3 (Tables 4.15 and 4.16) and it appears that the engineering works have significantly increased the pH values of the surface soil.

(3) There is no significant difference between GP 6 and both GP 4 and GP 5 (Tables 4.15 and 4.16) i.e. as with granite soils under eucalypt, there is similarly no significant change in pH values as a result of the engineering works through pine forest on granite soils.

(4) There is a significant difference between SP 6 and SP 4 but no significant difference between SP 6 and SP 5. Since there is no significant difference between SP 4 and SP 5 i.e. respectively steep and shallow slopes, the value at SP 6 indicated that the engineering works have caused a significant change in the pH value. In as much as site SP 5 is an area with a naturally steep slope it is concluded that the engineering works in pine forest over shale soils with a steep slope have significantly increased the soil pH.

Thus engineering works through a vegetative cover of eucalypt and pine have changed the soil state on the shale soil but not the granite soil.

The data in Table 4.15 and 4.16 also show significant changes in pH as a result of forest operations on the steep shale soils, i.e. the pH of SP 4 is significantly different to that at SE 1. A comparison for shallow slopes on the shale site was not available. On granite soil the data shows that there is no significant change in the pH state as a result of forest operations on the steep slope (compare GP 4 and GE 1) but there is a significant difference on the shallow slope (GP 5 and GE 2).

Thus forestry operations have had significant effects on the pH state of steep shale and shallow granite soils but no significant effect on steep granite soils.

4.3.7 Total Nitrogen and Phosphorus

Table 4.17 shows the mean values of total nitrogen and phosphorus levels for all sites.

TABLE 4.17 Mean Values of Total Nitrogen and Phosphorus

Property Site	Total Nitrogen (ppm)		Total Phosphorus (ppm)	
	Mean	S.E.	Mean	S.E.
GE 1	1822	447	332	21
GE 2	1670	202	234	27
GE 3	1101	137	256	24
GP 4	1510	130	365	14
GP 5	829	113	141	13
GP 6	539	82	217	9
SE 1	1405	112	191	5
SE 3	693	121	141	11
SP 4	1163	165	194	22
SP 5	700	126	144	23
SP 6	481	52	151	7

Under the same type of vegetation and slope, both total nitrogen and phosphorus levels were lower on shale soil than on granite soil (GE 1 > SE 1, GP 4 > SP 4, GE 3 > SE 3 and GP 6 > SP 6). The difference was not significant at the 5% level in the case of nitrogen, but was highly significant at 0.1% level in the case of phosphorus, except for the phosporus level on shallow shale soil under pine (SP 5) which was slightly higher than the level on shallow granite soil under pine (GP 5). Within the same type of vegetation and geology, total nitrogen and phosphorus were lower on shallow slopes than on steep slopes (GE 2 < GE 1, GP 5 < GP 4 and SP 5 < SP 4).

Forest management practices, i.e., the changing of forest cover from eucalypt to pine, lowered N and P levels on both granite and shale soils. Phosphorus levels decreased on shallow slopes, but increased on steep slopes. However the statistical analysis shows that the changes were not significant at the 5% level.

These results generally support Hamilton's conclusion (op. cit. p. 48) that when dry sclerophyll forest is changed to establish radiata pine plantations, the levels of total nitrogen and total phosphorus are decreased. Hamilton suggested that this represented a decline in the fertility status of the surface soil.

Engineering practices and revegetation significantly lowered the total nitrogen compared to the nearby forest. Phosphorus levels along the gravity main were also decreased on steep slopes (GE 1 > GE 3, GP 4 > GP 6, SE 1 > SE 3) but were increased on shallow slopes (GE 2 < GE 3, GP 5 < GP 6 and SP 5 < SP 6) when compared to adjacent forest areas. The data does not therefore enable a general conclusion to be made regarding the effect of engineering construction and revegetation on phosphorus levels.

4.3.8 Total Cations

Seven cation levels (K, Na, Zn, Mg, Ca, Mn, Fe) were investigated and the mean values of total monovalent and divalent cations calculated (Table 4.18) for all sites.

On soils of the same slope under the same type of vegetation, total cation levels on shale soils were higher than for granite soils. Total cations on shallow slopes are lower than on steep slopes for the same vegetation type, as was the case with nitrogen and phosphorus (GE 2 < GE 1, GP 5 < GP 4 and SP 5 < SP 4).

The total cations level under eucalypt was higher than the level under pine on the same type of soil and slope (GE 1 > GP 4, GE 2 > Gp 5 and SE 1 > SP 4). The levels on the gravity main revegetation were higher than the levels under pine and eucalypt for the same soil (GE 3 > GE 1 and GE 2, GP 6 > GP 4 and GP 5, SE 3 > SE 1 and SP 6 > SP 4 and SP 5).

Divalent cations increase soil aggregation and thus increased concentrations of divalent cations would decrease erodibility (Kemper and Chepil, op. cit. p. 17 ; Wallis and Stevan, 1961).

The percentage of total divalent cations on granite soil was higher than the level on the shale soil under the same vegetation and slope (GE 1 > SE 1, GP 4 > SP 4 and GP 5 > SP 5). Granite soils, with a higher aggregation than shale soils for the same vegetation and slope, thus have a lower risk of erosion.

TABLE 4.18 Mean Cations Per Site

Parameter / Site	Cations - ppm									Total Mono-valent cations (%)	Total Divalent cations (%)
	K	Na	Zn	Mg	Ca	Mn	Fe	Total Mean	Total S.E.		
GE 1	6611	83	39	4059	1307	441	22043	34583	1638	19.35	80.65
GE 2	7388	94	20	2378	1117	442	17161	28600	1034	26.16	73.84
GE 3	8832	116	37	3644	1091	339	22593	36652	1288	24.41	75.59
GP 4	9066	224	32	2621	2741	814	16552	32050	1395	28.99	71.01
GP 5	3303	154	14	1217	793	286	9569	15336	2149	22.54	77.46
GP 6	5895	129	55	3633	1124	314	23442	34592	2067	17.41	82.59
SE 1	8316	289	32	1984	298	41	24766	35726	1970	24.09	75.91
SE 3	10893	209	145	4715	228	114	26477	42781	1465	25.95	74.05
SP 4	10374	265	20	2296	1050	265	20305	34575	1854	30.77	69.23
SP 5	7659	153	13	1534	982	275	12528	23144	2079	33.75	66.25
SP 6	11959	267	36	2587	215	62	24894	40020	1453	30.55	69.45

The percent divalent cations under eucalypt was higher than the percentage under pine on the steep slopes of both granite and shale soils, but was lower on the shallow slopes. The soil under eucalypt on steep slopes thus shows better aggregation than under pine, and the soil under eucalypts on shallow slopes shows lower aggregation than under pine. On this basis reafforestation on steep slopes increases the risk of erodibility and afforestation on shallow slopes decreases the risk of erodibility.

The levels of divalent cations on the gravity main sites were similar to those in the soil of the nearby vegetation, except on GP 6 where the divalent cations level was much higher than GP 4 or GP 5. The engineering constructions and revegetation do not markedly affect the aggregation and hence the risk of erosion is unchanged.

4.4 INDICES OF SOIL ERODIBILITY

4.4.1 Dispersion Ratio

Middleton (op. cit. p. 21) found that the properties of soil giving the best index of erosiveness were:- the dispersion ratio, the ratio of colloid content to moisture equivalent, the erosion ratio, and the silica-sesquioxide ratio. Middleton, in discussing the validity of these ratios, stated that the dispersion ratio was probably the most valuable single criterion in distinguishing between erosive and non-erosive soils. Susceptibility to erosion increased with increasing values of the dispersion ratio, and he found values were generally above 15 for "erodible soils" and below 15 for "non-erodible" soils. Since Middleton's work, the dispersion ratio has been used frequently and confirmed as a significant indicator of erodibility by Lutz (op. cit. p. 22); Middleton and Slater (1935); Anderson (op. cit. p. 21); Andre and Anderson (1961); Wallis and Stevan (op. cit. p. 109); Olson and Wischmeier (1963) and Chhetri (op. cit. p. 29).

On the basis of Middleton's dispersion ratios, all the soils within the study area are "erodible" soils (Table 4.19).

TABLE 4.19 Mean Dispersion Ratio for the Site

Site	Dispersion Ratio	
	Mean	95% Confidence Limits
GE 1	36.75	± 6.16
GE 2	36.76	± 7.95
GE 3	31.65	± 3.62
GP 4	34.20	± 3.64
GP 5	36.75	± 11.45
GP 6	38.17	± 2.22
SE 1	17.37	± 2.71
SE 3	33.92	± 5.32
SP 4	30.15	± 7.65
SP 5	47.72	± 8.63
SP 6	30.44	± 4.30

There are significant differences in the dispersion ratio between sites (Table 4.20) at GP 6, SP 5 and SE 1, the eucalypt area on shale soil, where the ratio is much lower. The data thus indicates:-

TABLE 4.20 Summary of Significant Differences Between Dispersion Ratio Values (Student's 't' test)

	Granite						
	6	5	4	3	2	1	
1	NS	NS	NS	NS	NS		1
2	NS	NS	NS	NS			2
3	**	NS	NS			***	3
4	*	NS		NS		**	4
5	NS		*	*		***	5
6		***	NS	NS		***	6
	6	5	4	3	2	1	
	Shale						

NS - Not significant at p = 0.05
* - Significant at p = 0.05
** - Significant at p = 0.01
*** - Significant at p = 0.001

1 = Eucalypt - Steep Slope
2 = Eucalypt - Shallow Slope
3 = Eucalypt - Gravity Main
4 = Pine - Steep Slope
5 = Pine - Shallow Slope
6 = Pine - Gravity Main

TABLE 4.21 Mean Clay Ratio for the Sites

Site	Clay Ratio	
	Mean	95% Confidence Limits
GE 1	10.66	± 1.33
GE 2	5.73	± 0.73
GE 3	5.32	± 1.35
GP 4	8.35	± 1.04
GP 5	8.02	± 2.30
GP 6	7.64	± 0.64
SE 1	3.58	± 0.44
SE 3	4.58	± 0.24
SP 4	4.93	± 0.41
SP 5	8.98	± 3.91
SP 6	4.37	± 0.48

(1) the shale soil under eucalypt appears more stable than at any other site;

(2) there is little difference in erodibility of soil of granite origin; and

(3) the soil of shale origin may be more liable to erode when the eucalypts are replaced because of forest and engineering practices.

4.4.2 Clay Ratio

The mean values of the clay ratio for all sites are given in Table 4.21

Bouyoucos (op. cit. p. 22) proposed that the clay ratio should be used to evaluate erodibility, instead of the erosion ratio, because it was "simple, logical and more scientific". Studies by Bouyoucos showed that the clay ratio was smallest in non-erosive soils and greatest in erosive soils.

In this study, clay ratio values on granite soils were 10.66 and 5.73 under eucalypts, 8.35 and 8.02 under pines, and 5.32 and 7.64 under revegetative grasses respectively. On shale soils the mean values were 3.58 under eucalypt, 4.93 and 8.98 under pines, and 4.58 and 4.37 under grasses. The mean values on shale soil were lower than the values on granite soil indicating lower susceptibility to erosion, except at SP 5 where the clay ratio was much higher than for shale soils at other sites. Although clay ratio values varied significantly from site to site (Table 4.22), no clear difference was caused by change of vegetative cover on granite soils. There was a highly significant increase in clay ratio values on shale soils on changing the vegetative cover from eucalypt to revegetated grasses, and significant successive increases by changing to pine and then revegetated grasses.

TABLE 4.22 Summary of Significant Differences Between Clay Ratio Values (Student's 't' test)

	Granite						
	6	5	4	3	2	1	
1	***	*	**	***	***		1
2	***	NS	***	NS			2
3	**	*	***			***	3
4	NS	NS		NS		**	4
5	NS		**	*		***	5
6		***	NS	NS		***	6
	6	5	4	3	2	1	
	Shale						

Thus the data indicates that:-

(1) the soil of granite origin, with a higher clay ratio, is more erodible than shale soil;

(2) the soil on granite does not become more erodible because of forestry and engineering practices;

(3) there is a significant increase in erodibility of shale soils when the dry sclerophyll forest cover is changed to either pine or grass; and

(4) there is a significant increase in erodibility when pine is changed to grass.

4.4.3 Porosity and Surface Soil Bulk Density

The mean values of the surface soil bulk density, total porosity and non-capillary porosity of all sites are given in Table 4.23.

Surface soil bulk densities under mature pine forest were significantly less (Table 4.24) than bulk densities under mature

TABLE 4.23 Mean Values of Bulk Density (Surface Soil) and Porosity

Parameter / Site	Bulk Density (Surface Soil) gm/cc		Total Porosity (%)		Non-Capillary Porosity (%)	
	Mean	S.E.	Mean	S.E.	Mean	S.E.
GE 1	1.17	0.07	37.13	3.02	31.86	3.09
GE 2	1.15	0.04	39.08	1.71	31.98	1.12
GE 3	1.40	0.05	24.65	2.35	18.55	2.89
GP 4	1.13	0.04	39.14	2.23	31.28	1.87
GP 5	1.12	0.05	42.90	2.52	33.65	2.36
GP 6	1.43	0.04	25.06	2.83	12.95	2.61
SE 1	1.21	0.01	34.71	1.03	29.96	1.12
SE 3	1.47	0.05	31.28	4.35	26.15	4.56
SP 4	0.99	0.01	42.58	2.59	37.36	2.64
SP 5	1.15	0.02	42.63	1.72	36.14	2.51
SP 6	1.21	0.01	42.35	1.39	32.04	1.71

stands of eucalypt only on shale soils (SE 1 > SP 4 and SP 5). They were also lower, but not significantly so, for the granite soils. Surface soil bulk densities were significantly greater at all sites where there had been engineering works, when compared to adjacent sites (GE 3 > GE 1 and GE 2, GP 6 > GP 4 and GP 5, SE 3 > SE 1 and SP 6 > SP 4 and SP 5).

Mean values of both total porosity and non-capillary porosity were correlated with mean values of surface bulk density and the correlation was highly significant ($p = 0.001$). The tests for significant difference between sites (Table 4.24) for bulk density, total porosity and non-capillary porosity showed the same trend on the granite but not on the shale.

TABLE 4.24 Summary of Significant Differences in Bulk Density and Porosity of Surface Soil (Student's 't' test)

a - Bulk Density

	Granite						
	6	5	4	3	2	1	
1	**	NS	NS	*	NS		1
2	***	NS	NS	**			2
3	NS	**	***			***	3
4	***	NS		***		***	4
5	***		***	***		*	5
6		*	***	***		NS	6
	6	5	4	3	2	1	
	Shale						

b - Total Porosity

	Granite						
	6	5	4	3	2	1	
1	*	NS	NS	**	NS		1
2	***	NS	NS	***			2
3	NS	***	***			NS	3
4	**	NS		*		*	4
5	***		NS	*		**	5
6		NS	NS	*		***	6
	6	5	4	3	2	1	
	Shale						

c - Non-Capillary Porosity

	Granite						
	6	5	4	3	2	1	
1	***	NS	NS	**	NS		1
2	***	NS	NS	***			2
3	NS	**	**			NS	3
4	***	NS		*		*	4
5	***		NS	NS		*	5
6		NS	NS	NS		NS	6
	6	5	4	3	2	1	
	Shale						

1 = Eucalypt - Steep Slope
2 = Eucalypt - Shallow Slope
3 = Eucalypt - Gravity Main
4 = Pine - Steep Slope
5 = Pine - Shallow Slope
6 = Pine - Gravity Main

NS - Not Significant at $p = 0.05$
* - Significant at $p = 0.05$
** - Significant at $p = 0.01$
*** - Significant at $p = 0.001$

A soil with low density has a high porosity, a high rate of infiltration and a low susceptibility to erosion (Bennett, Harris, op. cit. p. 18). The bulk density and porosity results therefore indicate that the surface soil under mature pine plantation is less erodible than the surface soil under natural eucalypt stands on both granite and shale soils. On the other hand soils which have undergone engineering works show significantly increased surface bulk densities (and significantly decreased porosities) and are thus more liable to erode than undisturbed surface soils under the mature forest stand of pine and eucalypt.

4.4.4 Stone or Coarse Particle Content

In this study, aggregates >2mm (gravel) were sieved out in the dry stage, and mean values of all sites calculated (Table 4.25).

TABLE 4.25 Mean Gravel Content of the Site

Site	Mean Gravel Content by Weight	
	(Percent)	95% Confidence Limit
GE 1	37.43	± 9.01
GE 2	25.70	± 6.74
GE 3	36.05	± 5.40
GP 4	26.56	± 11.03
GP 5	12.68	± 3.40
GP 6	25.51	± 6.55
SE 1	48.57	± 6.50
SE 3	45.70	± 6.79
SP 4	47.33	± 6.74
SP 5	39.02	± 5.47
SP 6	37.41	± 7.02

The soil of shale origin is more stony than the soil of granite origin (SE 1 $>$ GE 1, SP 4 $>$ GP 4, SP 5 $>$ GP 5, SE 3 $>$ GE 3 and SP 6 $>$ GP 6). Although not significant at the 5% level, the soil on steep slopes contained more gravel than the soil on shallow slopes under similar types of vegetation (GE 1 $>$ GE 2, GP 4 $>$ GP 5 and SP 4 $>$ SP 5) indicating that the erodible smaller aggregates had been washed away on steep slopes. A comparison of sites (GE 1 and GE 3, GP 4 and GP 6, and SE 1 and SE 3, SP 4 and SP 6) shows no significant differences and the data indicate that forestry management and engineering practices have not affected the proportion of the soil with particle size $>$ 2mm.

A number of workers have investigated the weight of water-stable aggregates as a measure of erodibility (Adams et. al., Wooldridge, Farmer and Van Havern, op. cit. Sect. 2.4.3). Bryan (op. cit. p. 19) concluded that the percentage weight of water-stable aggregates greater than 3mm was the most reliable index to show the correct order of erosion in each case he studied. In this study soil of shale origin is more stony than the soil of granite origin and although this is based on a separation size of 2mm, it indicates in relation to Bryan's work that granite soil is more likely to be eroded than shale soil. That the soil of steep slopes contained more gravel than soil on shallow slopes similarly indicates that the surface soils of the shallow sites are more erodible than on the steep slopes. However, the magnitude of slope can of course influence the erosion that actually takes place.

4.4.5 Organic Matter Content

Soil organic matter is an important factor in the control of aeration, water-holding capacity, and granulation of field soils. It constitutes only a small part of total weight in mineral soils but most of the organic matter is found in the top soil and any erosion that occurs will result in significant organic matter losses.

The mean percentage of Loss-on-Ignition (% LoI) is given in Table 4.26 for all sites.

TABLE 4.26 Mean % Loss-on-Ignition

Site	% LoI		
	Mean	95% Confidence Limits	
GE 1	6.61	4.95	8.26
GE 2	7.88	6.93	8.83
GE 3	5.42	4.88	5.97
GP 4	7.33	5.68	8.97
GP 5	4.12	3.05	5.19
GP 6	4.54	3.54	5.54
SE 1	11.80	10.66	12.94
SE 3	5.40	3.77	7.03
SP 4	8.83	6.90	10.75
SP 5	5.28	5.10	5.46
SP 6	4.95	4.54	5.36

The mean values of % LoI on steep and shallow slopes on granite under eucalypt (GE 1 and GE 2) were within the same range. For the same slopes under eucalypt, shale soil was significantly higher than for granite soil (SE 1 > GE 1). LoI % was significantly higher on steep slopes under pine on soil of both shale and granite origin (GP 4 > GP 5 and SP 4 > SP 5). For the same slopes there was no significant difference between pines on shale and on granite soils (GP 4 and SP 4, GP 5 and SP 5). Change of vegetative cover from eucalypt to pine increased % LoI on steep granite slopes (GP 4 > GE 1) but % LoI was significantly decreased on shallow granite slopes (GE 2 > GP 5) and on steep shale slopes (SE 1 > SP 4). Gravity main revegetated sites showed no significant difference between shale and granite soils (GE 3 and SE 3, GP 6 and SP 6), but the mean % LoI was lower than nearby sites except for GP 5 which had the lowest mean % LoI within the study area.

Hamilton (op. cit. p. 48) investigated the loss on ignition in six pairs of plots located at Kowen, Pierces Creek and Brindabella ranges, in the A.C.T. The results of the experiment confirmed the work of Hamilton who found that the soil in the dry sclerophyll forest areas on which pines (Pinus radiata) had been established showed a considerable fall in Loss-on-Ignition values.

The presence of organic matter and lime, in soils with the smaller particles aggregated into granules, enables water absorption to occur more quickly than the same soil in the non-granulated state, and they are more resistant to dispersion and erosion (Baver, op. cit. p. 7). However McCalla (1945) concluded that quantity of organic matter may not be as important as quality in producing stability to water drops. A number of workers have found an inverse relationship between % LoI and erodibility (Williams and Cooke, 1961; Bryan, op. cit. p. 19 ; Balci, op. cit. p. 33).

The soils studied have higher organic matter content on steeper slopes than soil on shallow slopes regardless of soil origin and vegetation type, this being most marked under pine stands. On the basis of the findings of the workers cited above the soils on steeper slopes would have higher aggregation and be less susceptible to erosion. The organic matter content of granite soils does not appear to change when pine forest is established on the dry sclerophyll forest sites but the organic matter is significantly lowered if the soil is of shale origin. Thus, and again on the basis of the reported findings, afforestation on shale soils would increase the risk of erodibility. Engineering practices investigated in this study generally caused the organic matter content to decrease on both types of soils but the changes were not highly significant. Thus, again on the basis of the reported findings, the engineering works did not significantly change the susceptibility of the surface soil to erosion.

4.4.6 Aggregate Stability

Mean values of the number of water drops required to start breaking, and to destroy, the soil aggregates are shown in Table 4.27.

The number of water drops required to start breaking the aggregate is highly correlated ($p = 0.001$) with the total number of water drops required to destroy them.

TABLE 4.27 Summary of Aggregate Stability of Surface Soil

Site	Nos. of Water Drops/0.1 gm Soil			
	Start to break Mean	To destroy 95%		
		Mean	Confidence	Limits
GE 1	22.7	43.3	26.0	60.6
GE 2	13.4	24.8	14.6	35.0
GE 3	8.0	18.5	14.8	22.3
GP 4	13.7	22.5	17.2	27.8
GP 5	8.7	18.2	14.6	21.7
GP 6	4.1	10.4	9.4	11.4
SE 1	15.6	31.3	27.7	34.9
SE 3	7.1	15.7	12.9	18.5
SP 4	12.7	24.9	21.1	28.8
SP 5	9.7	18.8	15.7	21.8
SP 6	6.0	12.6	9.8	15.3

Bryan (op. cit. p. 19) concluded that aggregation is the most important soil property governing resistance to erosion in many soils, and the most profitable field for further study in indexing soil erodibility would be aggregate stability and distribution. The soil aggregates on steep slopes seem more stable than the aggregates on shallow slopes on both soil types if under the same type of vegetative cover (GE 1 > GE 2, GP 4 > GP 5, and SP 4 > SP 5) but the differences are not significant at the 5% level. The soil under eucalypt is more stable than the soil under pine for the same type of soil and slope (GE 1 > GP 4, GE 2 > GP 5, SE 1 > SP 4) but the differences are again not significant at 5% level. The stability of soil aggregates at the sites on the gravity main is significantly lower (5% level) than nearby sites, on soils of both granite and shale origin (GE 3 < GE 1, GP 6 < GP 4 and GP 5, SE 3 < SE 1, and SP 6 < SP 4 and SP 5).

4.5 SUMMARY OF RESULTS

The results and findings regarding the soil properties and erodibility indices investigated in this study are summarized in terms of land use at the sites (Table 4.28).

TABLE 4.28 Summary of Results

Soil Properties and Indices of Erodibility	RESULTS			
	All Sites	Dry Sclerophyll Forest	Reafforested Sites	Engineering Construction sites (Gravity Main)
Vegetative Cover	Granite soil sustained a greater vegetative ground cover than soil of shale origin.	The crowns were mostly free from each other because of uneven and sparse spacing. Ground vegetative cover provided soil stability on both types of soil.	Pine forest, although thinned three years earlier, provided a canopy cover comparable with dry sclerophyll forest. Pine forest produced the best vegetative ground cover on both types of soil. Ground vegetative cover provided soil stability on both types of soil.	No canopy cover of trees. Ground vegetative cover maintained soil stability on both types of soil.
Forest Litter and Soil Invertebrates	There were significant populations of soil invertebrates at each site.	Eucalypt forests accumulated a biomass of forest litter sufficient to control surface runoff and soil loss on both types of soil.	Pine forests also accumulated a biomass of forest litter sufficient to control surface runoff and soil loss on both types of soils.	No observations
Soil colour		The colour at the study sites were within the same range except at SE 1A where the HUE was 7.5 YR instead of 10 YR.	The range in colour was the same as for the eucalypt forest.	Soil colour was markedly different from the soils under pine and eucalypt and indicated a lower content of organic matter. This would effect a decrease in the structural stability of the soil.

TABLE 4.28 (Cont'd)

Soil Properties and Indices of Erodibility	RESULTS			
	All Sites	Dry Sclerophyll Forest	Reafforested Sites	Engineering Construction sites (Gravity Main)
Penetration	Compaction of granite soil was lower than for shale soil. Compaction was lower on shallow slopes than on steep slopes.	Compaction was lower than at either the pine or revegetated grass sites for both types of soil.	Penetration was slightly higher than the values with eucalypt cover for both granite and shale soils.	Highest compaction compared to nearby forest indicating the lowest porosity.
Particle Size Distribution	There was no marked difference in particle size distribution within the same type of vegetation and soil origin. The percentage of clay particle content was higher on shale than granite, but was not significant at all sites.	A higher percentage content of clay particles compared to pine or grass indicating lower erodibility status.	Significant decreases in clay particle content indicating a higher erodibility status.	Significant decreases in clay particle content showing a higher erodibility status compared to eucalypt and pine.
Dispersion	The total (silt + clay) and dispersed (silt + clay) were not correlated. Soils on the shallow slopes were more dispersed than those on steep slopes. There were no significant differences in dispersion between sites on granite soils.	The soils at the eucalypt sites were less dispersed than those at the pine and revegetated grass sites on shale.	Higher dispersion on shale than granite soil.	Dispersion higher than for eucalypt on shale soil.

TABLE 4.28 (Cont'd)

Soil Properties and Indices of Erodibility	RESULTS			
	All Sites	Dry Sclerophyll Forest	Reafforested Sites	Engineering Construction sites (Gravity Main)
Soil Moisture	There were no significant differences between sites.			
Soil Reactor (pH)	The pH values on shale soils were lower than the values on granite under the same type of vegetation and slope.	The values were more acidic on shale soil than granite.	Reafforestation caused a significant increase in the pH of steep shale and shallow granite soils, but no significant effect on steep granite soils.	Engineering construction increased the pH of shale soil but not of granite soil.
Total Nitrogen and Phosphorus	Total nitrogen and phosphorus levels were lower in shale soils than granite soils under the same type of vegetation and slope. Total nitrogen and phosphorus were lower on shallow slopes than steep slopes.	Both phosphorus and nitrogen levels were higher than on pine and grass sites on both types of soil.	Both nitrogen and phosphorus levels were lowered on granite and shale soils.	The nitrogen level decreased on all sites. Phosphorus levels were lowered on steep slopes but raised on shallow slopes.
Total Cations	Total cations levels were higher on shale than granite soil, under the same type of vegetation and slope. Total cations levels were lower on shallow slopes than on steep slopes.		Total cations levels were lowered.	Total cations levels were higher than nearby sites.

TABLE 4.28 (Cont'd)

Soil Properties and Indices of Erodibility	RESULTS			
	All Sites	Dry Sclerophyll Forest	Reafforested Sites	Engineering Construction sites (Gravity Main)
Total Cation (Cont'd)	The percentage of total divalent cations was higher on granite than shale under the same type of vegetation and slope, indicating a lower risk of erosion.	The divalent cations percentage was higher on steep slopes but lower on shallow slopes when compared to pine.	Reafforestation on steep slopes increased the risk of erodibility and afforestation on shallow slopes decreased the risk of erodibility on the basis of total divalent cations percentage.	The engineering constructions and revegetation did not markedly change the total percent divalent cations and hence the risk of erodibility was unchanged.
Dispersion Ratio	On the basis of Middleton's dispersion ratio value, all soils within the study area were '<u>erodible</u>'.	The shale soil under eucalypt was more stable than at any other site. There was no significant difference in the ratio between sites on soil of granite origin, but the ratio was significantly lower on steep shale than steep granite.	The soil of shale origin became more susceptible to erosion when eucalypts were replaced by pines.	The soil of shale origin became more susceptible to erosion.
Clay Ratio	Shale soils were less susceptible to erosion than granite soil.	The mean value of the clay ratio was significantly lower on steep shale than on steep granite indicating that the risk of erosion was lower. The values also indicated that granite shallow slopes were more stable than steep slopes.	Granite soil did not become more erodible, but there was a significant increase in the erodibility of shale soil.	Granite soil did not become more erodible but there was a significant increase in the erodibility of shale soil.

TABLE 4.28 (Cont'd)

Soil Properties and Indices of Erodibility	RESULTS			
	All Sites	Dry Sclerophyll Forest	Reafforested Sites	Engineering Construction sites (Gravity Main)
Bulk Density and Porosity	Mean values of both total porosity and non-capillary porosity were highly negatively correlated ($p = 0.001$) with mean values of surface bulk density.	The bulk density was lower and porosity higher on granite soils than on shale soils. Porosity of granite soils was lower on steep slopes than on shallow slopes. The porosity was lower compared to pine and higher compared to revegetated grass.	The bulk density was significantly lowered on shale soils but not significantly lowered on granite soils. The decrease in bulk density and the increase in porosity indicated that the surface soil was less erodible.	The bulk density was significantly increased indicating that the soils were more liable to erode than undisturbed soil under a mature stand of pine and eucalypt.
Stone or Coarse Particle Content	The values indicated that granite soil was more likely to be eroded than shale soil and shallow slopes were more liable to erode than steep slopes.	There were no significant differences between sites on granite soil with different slopes, or between steep shale and steep granite slopes.	Reforestation did not affect the coarse particle content.	Engineering construction did not affect the coarse particle content.
Organic Matter Content	The results indicated that the soils on steeper slopes had the highest aggregation and would therefore be less susceptible to erosion.	The organic matter content was not significantly different between sites on granite. The values for shale soils on steep slopes were significantly higher than for granite soils on steep slopes.	The results confirmed the work of Hamilton who found that the soil on which *Pinus radiata* had been established in the dry sclerophyll forest area had shown a considerable fall in Loss-on-Ignition values. The results also indicated that reforestation on shale soils increased the risk of erodibility.	The results indicated that the engineering construction and re-vegetation did not significantly change the susceptibility of the surface soil to erosion.

TABLE 4.28 (Cont'd)

Soil Properties and Indices of Erodibility	RESULTS			
	All Sites	Dry Sclerophyll Forest	Reafforested Sites	Engineering Construction sites (Gravity Main)
Aggregate Stability	The soil aggregates on steep slopes were more stable than the aggregates on shallow slopes but the differences were not significant at the 5% level.	There were no significant differences in aggregate stability between sites or between soil types.	The soil aggregates were less stable than the soil under eucalypts but differences were not significant at the 5% level.	The aggregate stability was significantly lower (5% level) than at nearby sites.

CHAPTER 5

REVIEW AND CONCLUSIONS

5.1 INTRODUCTION

Change in forest land use is a continuing process over extensive areas of Australia's forest estate. Changes in both soil properties and the susceptibility to erosion may occur as a consequence and it is important to assess the significance of the alterations in planning the land use changes.

In this study the effects on selected soil properties and indices of erodibility of reafforestation of dry sclerophyll forest with *Pinus radiata* and the construction of major engineering works in both the dry sclerophyll forest and the plantation have been investigated.

The effects of land use changes have been documented by many workers. In particular soil erodibility has been examined for many years and a number of parameters suggested as measures of the erodibility. The selection of the soil properties and indices of erodibility investigated was based on the results of these workers and directed toward assessing the effects of the land use changes on two major soil types, granite and shale. However the most efficient parameters to assess the significance of changes in land use on soil properties, and in particular erodibility, are still at issue, and thus a second important objective of this study was to evaluate the selected properties as measures of changes in land use.

The difficulties encountered by many workers in determining acceptable indices of erodibility are illustrated by the results from this study in that some of the soil properties measured do not indicate a change even with such a drastic land use change as the construction of the pipeline. Such results cast doubts on the suitability of measurement of these properties as practical methods for assessing changes in forest land use.

5.2 EVALUATION OF SOIL PROPERTIES AS MEASURES OF THE EFFECTS OF CHANGES IN FOREST MANAGEMENT ON SOIL ERODIBILITY

A number of the properties measured in this study showed no significant changes among the forest land uses investigated and while they may be useful for other purposes, it is concluded that these properties are not suitable parameters for the assessment of changes in erodibility arising from changes in forest land use. The properties are (Tables 4.7 and 4.14) -

- Soil colour
- Soil moisture content

There are a number of apparent anomalies in the results. For example, Table 4.19 shows that on the basis of the measured values of the Dispersion Ratio, steep slopes on both types of soil are less susceptible to erosion than shallow slopes. This is contrary to much empirical field evidence. The results also suggest, again on the basis of the measured values of the Dispersion Ratio, that both of the soil types studied (granite and shale) are erodible but field observations revealed no active erosion.

The anomalies lie in the relative importance of the parameters used in assessing the effects of the land use changes and while soil properties may be indicative of relative susceptibility of erosion, there are often very important physical factors which may reduce the risk of erosion of normally erodible soils. Four factors have been studied or noted, viz., vegetative cover, ground litter cover, slope and rainfall intensity.

That the erodible soils on the steep slopes of this study are not actually eroding suggests that, on granite and shale within the range of slopes investigated, ground cover is more important in determining actual erodibility status than both slope and physical soil properties. It is concluded that on the sites investigated changes in ground cover resulting from land use changes and the management of the ground cover are the most important determinants of changes in erosion.

The results in this study suggest that the ranking of the sites investigated in terms of vegetative cover is:-

(1) Pine Forest

(2) Eucalypt

(3) Gravity Main Revegetation.

Thus mature pine forest can reduce the risk of erosion and the construction of engineering works can increase the risk of erosion even when considerable care is taken to establish a ground cover.

There are occasions, under the management regimes investigated in this study, when the physical properties of the soil become the paramount consideration in assessing changes in the risk of erosion. They are usually of relatively short term duration and would occur when the existing vegetation is removed or destroyed by, for example, fire or by mechanical or chemical means and before new vegetation has been re-established. This study, based on the reported result of other works, suggests that the measurement of soil properties is a suitable means to evaluate relative erodibilities of exposed soils.

In the study, the dispersion ratio and clay ratio varied in the same way at different sites, and showed a significant positive correlation ($p = 0.05$). This indicates that either ratio will serve equally well as an index of soil erodibility. Of the other indices, % LoI showed a highly negative correlation ($p = 0.02$) with the dispersion ratio and a high positive correlation ($p \approx 0.05$) with aggregate stability. The bulk density, total porosity and non-capillary porosity were also highly correlated ($p = 0.001$) with each other and bulk density was positively correlated ($p = 0.05$) with penetration. The study suggests therefore that combinations of measures of aggregate stability, dispersion ratio, penetration and organic matter content would provide indices for indicating relative erodibility under similar conditions, such as slope and rainfall.

Accepting the correlations determined from the measurements of soil properties made in this study, then measurement of LoI and penetration would provide a reasonable basis by assessing the liability to erosion if there has been a change in the erodibility of a soil as a consequence of changes in forest land use.

5.3 REVIEW OF RESULTS

The results are summarised in Table 4.28.

At all sites within the study area it was observed that ground cover was adequate to protect the soil from the detaching and transporting power of rainfall. Thus after reafforestation practices and engineering works accompanied by revegetation measures, sufficient ground cover developed to afford protection of the soil from rainfall impaction and hence reduce the likelihood of soil erosion. The pine forest sites had the maximum cover overall on both granite and shale soils. In all cases ground cover was greater on granite soils and it is concluded that these favour the development of vegetative ground cover to a greater extent than the soils of shale origin.

Changes in pH, fertility status and cations, as a result of the changes in land use, vegetation type and management, were found to vary according to differences in soil origin, slope and the land use change.

Soil reaction (pH) values on shale soils were lower than those on granite soil, under the same type of vegetation and slope. Both the establishment of pine plantations on formerly dry sclerophyll forest, and engineering works followed by revegetation, caused an increase in pH values, which however, was not critical since pH values were within the range of 5.1 and 5.8.

The presence of more divalent cations is likely to enhance aggregation and hence improve infiltration characteristics. The measurements of cations in this study therefore suggest that, other factors being equal, shale soil is more susceptible to erosion than granite and reafforestation and engineering increase the risk of erosion.

A decline in fertility status is indicated by the measured changes in nitrogen and phosphorus levels.

The levels of total nitrogen and phosphorus decrease when dry sclerophyll forest is changed to radiata pine plantation. The results also indicated that destruction of surface soil due to engineering works caused a decline in nitrogen and phosphorus levels in spite of fertilization and revegetation with low shrubs, grass and clover. This confirms the result of other works and, while the significance of this in terms of forest management is beyond the scope of this study, it is of critical importance to retain ground cover in perpetuity if erosion is to be prevented.

The penetration test indicated better infiltration on shallow slopes than steep slopes but the soil on shallow slopes is dispersed more than the soil on steep slopes. It is probable that the dispersed soil particles on the steep slopes had been eroded away to the shallow slope and movement of particles by raindrops would be greater on shallow than steep slopes. This would be offset by the greater energy, per unit volume of water, available to move particles down the steep slopes. Thus while dispersion measurement indicates that shallow slopes are more susceptible to erosion than steep slopes it is concluded that the effects of slope on erosion can be more important in determining erosion than soil properties.

Compaction is higher on the pipeline revegetation area than under both the pine and eucalypt forests but there were no significant differences between pine and eucalypt. Thus, on the basis of changes in compaction, the risk of erosion in a mature plantation is not significantly different to the dry sclerophyll it replaced, but engineering works have increased the risk of erosion.

On the basis of Middleton's Dispersion Ratio all the soils within the study area are erodible soils. Clay ratio, gravel content, percent LoI and dispersion all indicate that granite soil is more likely to be eroded than shale soil, given the same type of vegetation and slope. Soil of shale origin under eucalypt appears to be the least dispersed compared to granite and both soils under pine and pipeline revegetation.

The indices of erodibility, namely dispersion ratio, clay ratio, organic matter content (% LoI), and aggregate stability all indicated that, if exposed, soil of shale origin will be more liable to erode after eucalypts are replaced by pine plantations or removed by engineering works. Such practices increase the soil porosity but cause no significant change in gravel content.

In view of the general finding that, when exposed, the soil of shale origin is more liable to erode after eucalypts are replaced by pine plantations or removed by engineering works, field investigations were made on fire-breaks, clearings associatd with electricity transmission lines, access tracks, the pipeline bench and plantations within the study and surrounding areas. The areas inspected were generally well covered with vegetation with no signs of soil erosion.

In some sections of the fire-breaks there was a very spare vegetative cover and signs of sheet erosion were evident. Thus while the study has indicated that the shale soils may have become more prone to erosion, erosion is not occurring where there is a good canopy and ground cover.

5.4 APPLICATION OF RESULTS

Soil erosion is the result of inappropriate land use and management. Therefore to avoid erosion, it is necessary to assess the likelihood of erosion under various management practices, such as reafforestation, engineering construction and prescribed burning. The study suggests that an increase in the risk of erosion of exposed soil occurs after the replacement of eucalypt particularly on shale soils and that it is important to provide and retain ground cover in plantation establishment and engineering construction.

There is a need for a quick field method for assessing soil properties in relation to erodibility. The study indicated that while either Middleton's Dispersion Ratio or Bouyoucos' clay ratio, and penetration would achieve this, ground cover and slope must also be measured.

5.5 SUMMARY

Soil erodibility may be assessed either by actual measurement of soil-loss under controlled conditions <u>or</u> by the recognition of certain soil properties as indices of erodibility. A comprehensive review of previous work on soil erosion, with emphasis on the effects of forest management practices on soil erodibility, indicated that a large number of diverse properties have been suggested for the assessment of soil erodibility.

Selected parameters and some properties of soil were studied under different vegetation cover and soil origin and analysed in relation to the effects on them of plantation establishment and the construction of engineering works.

Within the study area, there was adequate ground cover to protect the soil from the detaching and transporting power of rainfall, and more than enough biomass of forest litter accumulated to control surface runoff and soil erosion.

On the basis of Middleton's dispersion ratios, all the soils within the study area are 'erodible' soils.

The clay ratio, gravel content and % LoI, indices all indicated that granite soil is more likely to be eroded than shale soil, given the same type of vegetation and slope.

Indices of soil erodibility, such as dispersion ratio, clay ratio, organic matter content (% LoI), and aggregate stability indicated that if exposed the soil of shale origin will be more liable to erode after eucalypts are replaced by pine plantations or removed by engineering works.

The study suggests that either Middleton's (1930) dispersion ratio or Bouyoucos (1935) clay ratio and penetration would serve as indices of erodibility.

The study demonstrates the critical importance of vegetative cover in modifying erosion, and that cover and slope may be more important in assessing erosion than to differentiate between soils of granite and shale origin. Nevertheless there are significant differences between the effects of reafforestation and engineering works on the properties of granite and shale and thus after soil classification, ground cover, slope and soil properties should all be measured for an accurate assessment of susceptibility to erosion.

APPENDIX I Vocabulary of Soil Science

(Abstracted from FAO Multilingual Vocabulary of Soil Science, 1966)

accelerated erosion - An increase in the rate of erosion, caused by the activities of man.

aggregate - Structural unit consisting of more than one primary particle.

air-dry - Moisture content in equilibrium with surrounding air.

alluvial - Deposited from flowing or still water.

available - Capable of being taken up by plants.

base level of erosion - The lowest level to which a stream can erode its bed.

bulk density (apparent density) - Mass of dry soil per unit volume.

capillary water - Water retained in pores primarily by surface tension.

carbon-nitrogen ratio - Weight ratio of organic carbon to total nitrogen.

catchment basin (drainage basin) - District drainaged by a river and its tributaries.

cation exchange - Replacement of a surface valence-held cation by another.

clay - Particles of diameter less than 0.002 mm.

clay-colloid - clay particles of diameter less than 0.001 mm.

clay fraction - Clay distinguished from coarser soil particles.

clay pan - Dense subsoil horizon high in clay content.

clod - Lump of soil material created by human disturbance.

APPENDIX I (Cont'd)

cohesion - The property of particles sticking together to form an aggregate.

consistence - The degree of cohesion of soil or soil aggregates; resistance to deformation; feel to the fingers.

crumb - Rounded, porous and soft aggregate up to 10 mm in diameter.

debris - Accumulation of broken rock, soil material, organic residues, etc.

degree of aggregation - Measure of the proportion in which aggregates are present.

degree of dispersion - Extent to which aggregates are broken down by a given treatment.

exchangeable - Describes ions capable of replacement in the absorbing complex.

exchange capacity - Milliequivalents of ions that can be absorbed by 100 g of material at a specific pH.

fallow - Condition of soil left without crop for a time.

field capacity - Water held in a well drained soil after excess has drained away and rate of downward movement has materially decreased.

film water - Water retained in layers thicker than one or two molecules on the surface of particles in unsaturated soil.

fine earth - Soil passing through 2 mm sieve without grinding primary particles.

gley - Mottling in the soil produced by partial oxidation and reduction of iron caused by intermittent waterlogging.

APPENDIX I (Cont'd)

granule - Rounded aggregate of irregular shape up to 10 mm in diameter which is hard and relatively non-porous.

gravel - Particles between 20 and 2 mm in diameter.

gully - Large channel cut by (intermittently) running water.

gully erosion - Erosion that cuts deep channels (gullies) into land.

horizon - Soil layer with features produced by soil-forming processes.

A horizon - The uppermost layers of a soil profile where accumulation of organic matter and eluviation commonly occur.

B horizon - Part of a soil profile below the A horizon; usually illuvial.

C horizon - Horizon of weathered rock material little affected by biological soil-forming processes.

D horizon - Unweathered rock below the C horizon.

F horizon (F layer) - Layer of (usually forest) soil consisting of partly decomposed plant residues.

G horizon - The horizon in which gley occurs.

H horizon (H layer) - Organic layer of (usually forest) soils with dark-coloured structureless humus.

eluvial horizon - layer from which material has been removed in solution or in water suspension and in which silt-and sand-size particles have become concentrated.

illuvial horizon - Horizon that has received material in solution or suspension from the upper part of the soil.

humus - The amorphous (colloidal) organic matter of soil.

hydromorphic - Developed in presence of excess water all or part of the time.

APPENDIX I (Cont'd)

immature - Lacking a fully developed profile.

infiltration - Movement of water into soil.

land slide - (1) Rapid movement down hill of a mass of soil, rock or debris;

(2) Mass of material that has slipped down hill.

leach - Remove soluble material by passing a liquid through soil.

litter - Leaves and other undecomposed residues lying loosely on the soil.

loam - Soil having clay and coarser particles in proportions which usually form a permeable, friable mixture.

loss on ignition - Loss in weight caused by heating to redness soil previously dried at 105^{o}C.

lower plastic limit - Minimum moisture content permitting deformation of a small soil sample without rupture.

manure - Animal excreta with or without straw or other litter.

mature - Having a fully developed profile.

maximum water-holding capacity - Amount of water retained by a shallow layer of soil in equilibrium with a water table at its lower surface.

mechanical analysis - Particle-size-analysis - the determination of fractions by weight or mass, based on the separation of primary soil particles into groups according to "effective" diameters.

mellow - Porous, softer than friable, without tendency to become compact.

APPENDIX I (Cont'd)

mineralization - Release of mineral matter from organic combination by decomposition.

moisture - Water that can be removed from soil by heating at 105^{o}C.

mor (raw humus) - Ao horizon unmixed with and sharply demarcated from the underlying mineral horizon. Consists of L, F and H horizons.

morphology - Pattern of horizons and their observable properties that make up the soil.

mull (mild humus)- Humus (most often forest humus) layer of mixed organic and mineral matter with a gradual transition to the underlying mineral horizon.

mycorrhiza - Symbiotic association of fungi and roots.

nutrient - Substance required for plant growth.

parent material - Unconsolidated material from which a soil is formed.

parent rock - The rock from which parent material is formed.

pedogenesis - The formation of soil from parent material.

permeability - Readiness with which air or water can pass through soil, in particular, coefficient in pertinent flow equation.

plastic - Capable of undergoing deformation without rupture.

plow (plough) sole - Layer of soil compacted by passage of the plow (plough).

porosity (pore space) - Fraction of the total soil volume not occupied by solid particles.

APPENDIX I (Cont'd)

capillary porosity - Volume of small pores in soil that hold water by capillarity.

non-capillary porosity - Volume of large pores in soil that do not hold water by capillarity.

primary particle (ultimate particle) - The single particle or organic micelle after complete dispersion of aggregates.

profile - Vertical section of soil showing sequence of horizons from surface to parent material.

rill erosion - Formation of small channels by the uneven removal of surface soil by running water.

sand - Particles of diameter 2-0.02 mm.

coarse sand - Particles of diameter between 2 and 0.2 mm.

fine sand - Particles of diameter between 0.2 and 0.02 mm.

sedimentation analysis - Separation of particles depending on rate of settling in a fluid.

sheet erosion - The gradual, uniform removal of surface soil by water.

shifting sand - Sand continuously moved by wind.

silica-sesquioxide ratio - The molecular ratio $SiO_2/(Al_2O_3 + Fa_2O_3)$ $= SiO_2/R_2O_3$.

silt - Particles of diameter 0.02 - 0.002 mm.

silt and clay - Particles smaller than 0.02 mm that do not readily settle out of water and can be separated by decantation.

soil creep - Slow movement of soil material under the force of gravity.

APPENDIX I (Cont'd)

sticky point - Maximum moisture content at which kneaded soil ceases to stick to a knife.

strip cropping - Practice of growing (different) crops in (alternate) strips along contours or across prevailing direction of wind.

structure - Arrangement of primary soil particles in aggregates.

subsoil - Part of a soil between the layer normally used in tillage and the depth to which most plant rooots grow.

talus (colluvium) - Detritus accumulated at foot of a steep slope.

texture - Composition of soil in respect of particle size distribution.

tilth - State of aggregation of soil after cultivation.

topsoil - The layer of soil moved in cultivation, the A horizon.

total exchangeable bases (s value) - Milliequivalents of exchangeable metallic cations in 100 g of absorbing complex.

upper plastic limit - Minimum moisture content at which soil will barely flow under a standard stress.

water logging - State of water content being higher than field capacity.

watershed - The topographic boundary separating the waters flowing into different rivers or drainage basin.

wilting point (wilting percentage) - The maximum moisture percentage of soil that will induce permanent wilting of plant.

APPENDIX II Description of Plots

No.	Plot	Cover Density %		Slope			Field observation notes
		Canopy	Ground	Aspect	Shape	Steepness	
1	GE 1A	65	72	NW	Concave	$21^{\circ}.00'$	Dry sclerophyll forest with E. rossii and E. macrorhyncha association. Good soil cover and some exposed rocks.
2	GE 1B	5	82	NE	Concave	$9^{\circ}.00'$	Lower edge of pipeline cutting with fair cover of grass.
3	GE 1C	85	98	NW	Concave	$16^{\circ}.30'$	Dry sclerophyll forest with pure E. macrorhyncha, very good ground cover and some few exposed rocks.
4	GE 2A	77	97	NW	Linear	$12^{\circ}.30'$	Dry sclerophyll with E. rossii and E. macrorhyncha association. Very good ground cover and tree distribution.
5	GE 2B	4	65	NW	Linear	$4^{\circ}.00'$	Upper edge of pipeline cutting; fair cover mainly with white clover.
6	GE 2C	55	100	NE	Linear	$8^{\circ}.00'$	Shallow gully area with excellent ground cover. Dominant species is E. mannifera.
7	GP 1A	50	90	NW	Concave	$23^{\circ}.0'$	Mature (40 yrs) pine forest with good soil cover of pine needle and low grass, good undergrowth,seedlings and some exposed rocks.
8	GP 1B	4	92	NE	Convex	$14^{\circ}.0'$	On pipeline cutting. Very good cover of grass and clover.
9	GP 1C	81	91	NE	Convex	$29^{\circ}.0'$	Mature pine forest with very vigorous seedlings underneath. Exposed rocks.
10	GP 2A	40	100	NW	Linear	$9^{\circ}.0'$	Mature pine forest with excellent ground cover of pine needle and grass. Young seedling - undergrowth because of previous thinnings.
11	GP 2B	7	81	SW	Concave	$6^{\circ}.0'$	Good soil cover with clover,grass and pine needle from nearby forest.

APPENDIX II (Cont'd)

No.	Plot	Cover Density %		Slope			Field observation notes
		Canopy	Ground	Aspect	Shape	Steepness	
12	GP 2C	51	100	NW	Concave	$5^{\circ}.0'$	Valley area with excellent ground cover of pine needle and grass. Good revegetation of young pine seedlings under mature pine forest.
13	SE 1A	49	58	NW	Convex	$25^{\circ}.0'$	Fair cover of litter and undergrowth. Exposed rocks. *E. rossii* and *E. macrorhyncha* association.
14	SE 1B	11	24	SW	Convex	$11^{\circ}.0'$	Very poor cover of grass, almost bare soil. Few shrubs grow especially at lower boundary of pipeline cutting.
15	SE 1C	58	64	NW	Convex	$20^{\circ}.30'$	Fair cover of leaf litter. Few undergrowth *Eucalyptus* seedlings and wild cherry. Dry sclerophyll forest with *E. rossii* and *E. macrorhyncha* association.
16	SP 1A	40	69	NW	Convex	$25^{\circ}.0'$	Fair soil cover, many exposed rocks. Thinnings done (3) years ago.
17	SP 1B	13	79	NW	Linear	$2^{\circ}.0'$	Good cover of grass and shrubs. Excellent revegetation of shrubs and pine seedlings along the edges of pipeline cuttings.
18	SP 1C	72	80	SW	Concave	$29^{\circ}.30'$	Good soil cover with undergrowth of pine seedlings and short grass. Some exposed rocks.
19	SP 2A	43	80	NW	Convex	$16^{\circ}.0'$	Good cover with pine needles and branches. Some exposed rocks. Thinning done (3) years ago.
20	SP 2B	-	72	NE	Linear	$4^{\circ}.0'$	Good soil cover of grass, clover, pine needles from nearby trees. Lower edge of pipeline cutting.
21	SP 2C	36	95	NW	Linear	$13^{\circ}.30'$	Very good ground cover with short grasses and pine needles. Pine seedlings undergrowth due to thinnings (3) years ago.

APPENDIX III Soil Mechanical Analysis by Modified Plummet Balance

Stage 1 Coarse sand %

1. Sieve soil through a 2mm sieve removing gravel, stones, twigs etc.
2. Weigh 25gr. (25 $\pm$ 0.1gm) of the air dried sieved soil into a 600ml beaker
3. Add 200ml deionised water
4. Add 5ml 1.0N NaOH (40gm NaOH.litre)
5. Stir with mechanical stirrer for 5 mins. at a reasonably high speed.
6. Transfer contents to plastic bottle
7. Add 300ml deionised water
8. Add 10ml 10% calgon (calgon = commercial Sodium hexameta-phospate)
9. Close cap tightly and shake bottles on shaker for two hours.
10. Remove bottles and separate contents through 72 mesh sieve (0.2mm). Gently work fine sand, silt and clay through the mesh using rubber capped glass rod and copious amount of deionised water from a wash-bottle. Volume should NOT exceed 1200ml.
11. Material which has passed through sieve is placed in a 1250ml sedimentation cylinder. Make up to 1250ml exactly
12. Remove coarse sand from sieve, place in a weighed evaporating dish
13. Dry overnight in oven at 105°C cool, weigh.

Calculate: coarse sand% = $\dfrac{\text{weight of sand} \times 100}{25}$

APPENDIX III (Cont'd)

Stage 2 Silt and clay %

14. Set up plummet balance - calibrate 0% with deionised water in a 1250ml cylinder and 100% in a NaCl solution (17.55gm/litre) in another cylinder

15. Measure a blank reading in a solution of 5ml NaOH, 10ml Calgon, 1235ml water (deionised). This reading is subtracted from all readings on soil suspensions, which represent percentage particulate matter in suspension at 25cm depth.

16. Agitate the suspension thoroughly with a long paddle

17. Note the time the suspension becomes still

18. Refer to table of settling times at different temperatures

19. Take temperature before the appropriate time

20. Move cylinder carefully beneath balance, and ease the plummet slowly into the suspension, taking care not to disturb the suspension unduly. Adjust the depth of immersion with knurled knob so that knot on the nylon string is exactly on the water surface. Read the pointer, and record this as % silt and clay.

21. Remove plummet and move cylinder carefully away for further period of time as determined from settling period table

22. Repeat 19 and 20. Record reading as % clay

23. Subtract reading 22 from reading 20 to give % silt.

Stage 3 % fine sand

24. Decant and discard remaining clay suspension

25. Wash fine sand into 400ml beaker with mark at 10cm from bottom. Fill with tap water to 10cm mark

APPENDIX III (Cont'd)

26. Agitate and after settling between 5 and 6 minutes, carefully decant the cloudy suspension, leaving the fine sand

27. Repeat procedure until the suspension is clear.

28. Place fine sand in a weighed evaporating dish, dry overnight at $105^{\circ}C$, cool and weigh.

29. Calculate: % fine sand = $\frac{\text{weight fine sand}}{25} \times \frac{100}{1}$

30. % coarse sand + % fine sand + % silt + % clay = 100

Deficiency = organic matter.

Settling Periods

25gm air dry soil, in a 1250ml sedimentation cylinder measured with a Plummet balance at 25cm depth.

Temp. $^{\circ}C$. of suspension	Silt + Clay Mins.	Silt + Clay Secs.	Clay Hrs.	Clay Mins.
16	13	20	22	05
17	12	55	21	27
18	12	30	21	02
19	12	30	20	25
20	12	00	20	00
21	11	40	19	35
22	11	15	19	10
23	11	15	18	32
24	10	50	18	07
25	10	38	17	42

APPENDIX IV A — Results from Mechanical Analysis of Fine Earths (Average of Five Samples for Each Plot)

No.	Plot	Mechanical Analysis of Fine Earths < 2 mm (%)					Texture
		Coarse Sand 2.0 – 0.2	Fine Sand 0.2 – 0.02	Silt 0.02–0.002	Clay < 0.002	Organic Matter	
1	GE 1A	48.61	16.22	16.10	6.20	10.87	Sandy Loam
2	GE 1B	51.78	19.96	11.00	12.50	4.76	" "
3	GE 1C	54.81	19.81	12.60	8.00	4.78	" "
4	GE 2A	36.83	18.96	19.00	11.80	13.41	" "
5	GE 2B	37.14	23.22	14.20	20.40	5.04	Sandy Clay Loam
6	GE 2C	28.17	21.35	22.60	14.40	13.48	Loam
7	GP 1A	42.18	16.78	23.20	11.20	6.64	Sandy Loam
8	GP 1B	46.99	24.14	13.10	11.20	4.57	" "
9	GP 1C	45.60	23.81	14.70	9.30	6.59	" "
10	GP 2A	45.93	25.23	14.40	8.20	6.24	" "
11	GP 2B	52.23	22.32	11.10	11.30	3.05	" "
12	GP 2C	26.29	23.18	27.00	16.10	7.43	" "
13	SE 1A	36.09	15.32	21.10	20.10	7.39	Sandy Clay Loam
14	SE 1B	34.68	22.11	22.70	17.40	3.11	Sandy Loam
15	SE 1C	40.72	14.36	16.60	21.00	7.32	Sandy Clay Loam
16	SP 1A	33.90	15.60	24.40	16.40	9.70	Loam
17	SP 1B	39.23	19.14	19.00	17.50	5.13	"
18	SP 1C	35.14	16.97	24.40	14.40	9.09	"
19	SP 2A	37.40	20.45	18.60	16.20	7.35	Sandy Loam
20	SP 2B	44.98	18.78	15.20	18.40	2.64	" "
21	SP 2C	55.26	17.43	14.40	6.80	6.11	" "

APPENDIX IV B Particle-Size Distribution of Surface Soil

(Individual Size Classes)

No.	Plot	Percentage Wt. of Particle Sizes					
		Coarse Particle >2 mm	Coarse Sand 2.0–0.20	Fine Sand 0.2–0.02	Silt 0.02–0.002	Clay <0.002	Organic Matter
1	GE 1A	47.90	25.33	8.45	8.39	4.27	5.66
2	GE 1B	35.72	33.28	12.83	7.07	8.04	3.06
3	GE 1C	26.89	40.07	14.48	9.21	5.85	3.50
4	GE 2A	33.75	24.40	12.56	12.59	7.82	8.88
5	GE 2B	36.34	23.64	14.78	9.04	12.99	3.21
6	GE 2C	17.63	23.20	17.59	18.62	11.86	11.10
7	GP 1A	39.84	25.38	10.09	13.96	6.74	3.99
8	GP 1B	18.59	38.25	19.65	10.67	9.12	3.72
9	GP 1C	13.28	39.54	20.65	12.75	8.07	5.71
10	GP 2A	9.65	41.50	22.80	13.01	7.41	5.63
11	GP 2B	32.42	35.30	15.08	7.50	7.64	2.06
12	GP 2C	15.69	22.17	19.54	22.76	13.58	6.26
13	SE 1A	43.08	20.54	8.72	12.01	11.44	4.21
14	SE 1B	45.70	18.83	12.01	12.33	9.45	1.68
15	SE 1C	54.05	18.71	6.60	7.63	9.65	3.36
16	SP 1A	44.58	18.79	8.64	13.52	9.09	5.38
17	SP 1B	45.86	21.24	10.36	10.29	9.47	2.78
18	SP 1C	50.07	17.55	8.47	12.18	7.19	4.54
19	SP 2A	42.95	21.34	11.67	10.61	9.24	4.19
20	SP 2B	28.95	31.96	13.34	10.80	13.07	1.88
21	SP 2C	35.08	35.87	11.32	9.35	4.41	3.97

APPENDIX IV C   Particle-Size Distribution of Surface Soil

(Cumulative Percentage)

Size (mm) / Plot	Soil Fraction				
	+ 2.00	+ 0.2	+ 0.02	+ 0.002	+ 0.0
GE 1A	47.90	73.33	81.45	90.07	94.34
GE 1B	35.72	69.00	81.83	88.90	96.94
GE 1C	26.89	66.96	81.44	90.65	96.50
GE 2A	33.75	58.15	70.71	83.30	91.12
GE 2B	36.34	59.98	74.76	83.80	96.79
GE 2C	17.63	40.83	58.42	77.04	88.90
GP 1A	39.84	65.22	75.31	89.27	96.01
GP 1B	18.59	56.84	76.49	87.16	96.28
GP 1C	13.28	52.82	73.65	86.22	94.29
GP 2A	9.65	51.15	73.95	86.96	94.37
GP 2B	32.42	67.72	82.80	90.30	97.94
GP 2C	15.69	37.86	57.40	80.16	93.74
SE 1A	43.08	63.62	72.34	84.35	95.79
SE 1B	45.70	64.53	76.54	88.87	98.32
SE 1C	54.05	72.76	79.36	86.99	96.64
SP 1A	44.58	63.37	72.01	85.53	94.62
SP 1B	45.86	67.10	77.46	87.75	97.22
SP 1C	50.07	67.62	76.09	88.27	95.46
SP 2A	42.95	64.29	75.96	86.57	95.81
SP 2B	28.95	60.91	74.25	85.05	98.12
SP 2C	35.08	70.95	82.27	91.62	96.03

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